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THESIS

**IMPLEMENTATION OF A MULTIPLE ROBOT
FRONTIER-BASED EXPLORATION SYSTEM AS A
TESTBED FOR BATTLEFIELD RECONNAISSANCE
SUPPORT**

by

Patrick A. Hillmeyer

June 1998

Thesis Advisor:

Xiaoping Yun

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**IMPLEMENTATION OF A MULTIPLE ROBOT FRONTIER-BASED
EXPLORATION SYSTEM AS A TESTBED FOR BATTLEFIELD
RECONNAISSANCE SUPPORT**

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Captain, United States Marine Corps
B.S., University of Minnesota, 1990

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

June 1998

ABSTRACT

Future military battlefields will see smaller forces responsible for ever increasing geographical areas. In addition, future conflicts will occur more often in urban or built-up areas. Both of these trends argue for some type of augmentation for initial reconnaissance, continued observation, and control of lines of communication and other key terrain features. Multisensor systems, mounted on a variety of robotic platforms, can provide this type of battlefield support where it is needed most. However, before costly decisions concerning the details of such systems can be made, basic research needs to be conducted regarding their most effective composition and utilization.

Prior to this time all multiple robot studies at this institution had only taken place in simulated environments. This thesis implements a real-world multiple robot system that uses a technique known as frontier-based exploration to explore and map a laboratory or office environment. In doing so, many previously hidden aspects of multiple robot systems, unnoticeable in simulation-only studies, become evident. The results developed here are compared to results obtained elsewhere involving other robotic platforms. This research lays the foundation for future research involving multiple robots interacting as a system in a real-world environment and acting towards a common or shared goal.

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I. INTRODUCTION

A. GENERAL

As the general downsizing of the military continues, the trend on future battlefields will be toward smaller units being responsible for scouting and securing larger areas. It is also predicted that, in the near future, 70 percent of the world's population will be in urban areas [Ref. 1]. As more and more of the general population moves into cities, future battlefields are more likely to be in urban or built-up areas. As these trends continue the need for some type of robotic support and augmentation for the small unit or individual on the ground will become greater.

Urban and built-up areas present some of the greatest challenges for military units in the areas of initial reconnaissance, continued observation, and control of lines of communication and other key terrain features. Multisensor systems, mounted on a variety of robotic platforms, can provide this type of battlefield support in areas where it is needed most. However, before making very costly decisions about the make-up of these systems it is imperative to conduct some basic research about the types of systems that are most cost effective and most efficient. This will allow the system designers to make intelligent decisions about the type and composition of systems that will be most useful on tomorrow's battlefield.

B. PROBLEM STATEMENT

As a reconnaissance system is designed there are several fundamental questions that must be asked and answered. In some missions, a large number of the simplest possible systems may be the right answer. This might be the case if all that is desired is simple detection of “something” with no detail other than the fact that there is “something” in the vicinity of the systems sensors. For other missions the best solution may be a smaller number of systems incorporating higher capability sensors, increased processing capability, improved communications resources, and greater mobility. This would be the case if the system were required to perform more complex tasks such as target identification, target tracking, or even target attack. Or perhaps the best system for the mission lies somewhere in-between these two extremes or is even a combination of them both. [Ref. 2]

This thesis will explore a comparison between the first and second options. A robotic mapping system was originally developed for a small number of very expensive, but very sensor capable, NOMAD 200 robots. By taking this same system and implementing it on a larger number of much less expensive, but less capable, NOMAD SCOUT robots the beginnings of a comparison between the two options will be possible.

In addition, many of the challenges and questions inherent to the development of a multiple robot mapping system are also present in any research involving multiple robots attempting to accomplish a common task. The problems of communication, coordination, and control apply similarly to multiple robot mine clearing systems and robotic weapon

platforms. It is hoped that the development of a multiple robot testbed can set the stage for further research in these areas at this institution.

C. OUTLINE OF THE THESIS

Chapter II provides a description of the platforms and sensors that were used for the research in this thesis, as well as the platforms used in previous work for comparison purposes. Chapter III discusses the other hardware and software common to this and other research that was used to provide connectivity and control within the systems. Chapter IV provides background on the techniques of robotic map building. Chapter V describes the exploration strategies and techniques used in this and other studies. Chapter VI describes the methods of integrating the work of multiple robots in a cooperative map making effort. Chapter VII presents the results that were obtained at the Naval Postgraduate School (NPS) based upon the system originally designed at the Naval Research Laboratory (NRL). Finally, Chapter VIII discusses the conclusions and recommendations for follow-on studies.

II. PLATFORMS AND SENSORS

This chapter provides background information so that the reader has an understanding of the NOMAD 200 and NOMAD SCOUT mobile robots and the similarities and differences between these two platforms. It will also describe the sensors available on each of the platforms, as well as some details concerning previous work done with the NOMAD 200 at both NPS and NRL. Figure 1 provides a relative size and shape comparison of the NOMAD 200 and NOMAD SCOUT.

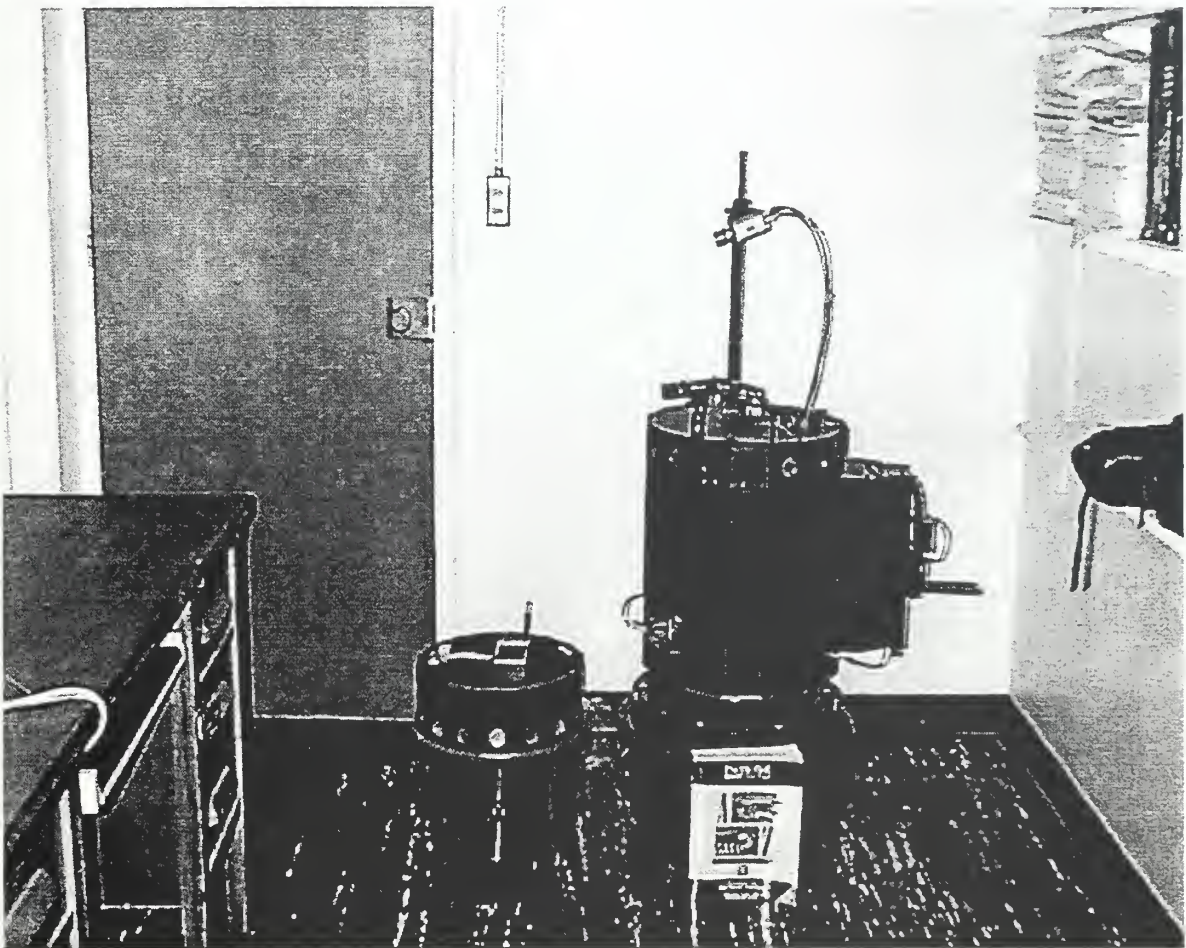


Figure 1. Relative size and shape comparison of the NOMAD SCOUT (left) and NOMAD 200 (right) – note telephone book in front of NOMAD 200 for reference.

A. NOMAD 200 MOBILE ROBOT

The NOMAD 200 is an integrated mobile robot system with four sensory modules including tactile, infrared, sonar and laser sensors. There are multiple onboard computers that provide sensor and motor control, as well as providing communication to the host computer via a wireless Ethernet system [Ref. 3]. Figure 2 provides a detailed picture of the NOMAD 200.

1. Mechanical Description

The NOMAD 200 base chassis is driven by a three-wheel synchronous drive mechanism, using one motor to drive all of the wheels and a second motor to steer all of the wheels. The robot has a zero gyro-radius, meaning that it can rotate about its own center. It can translate at up to 24 inches per second and rotate at a maximum rate of 60° per second. The base is 18 inches in diameter, which extends to 21 inches with the bumper installed. The NOMAD 200 stands 31 inches tall, excluding any additional sensors added on top of the robot [Ref. 4]. The turret (which all the sensor systems are mounted on) can be rotated independently of the base. [Ref. 4]

2. Sensor Systems

The basic NOMAD 200 sensor array includes tactile (bumper) sensors, infrared sensors, sonar sensors, and laser sensors. In addition to these sensor systems, the robot also has an odometric system that tracks the robot's movements. The encoder resolution

on this odometric system is 18 counts/cm for translation and 1510 counts/degree for robot steering and movement of the turret.

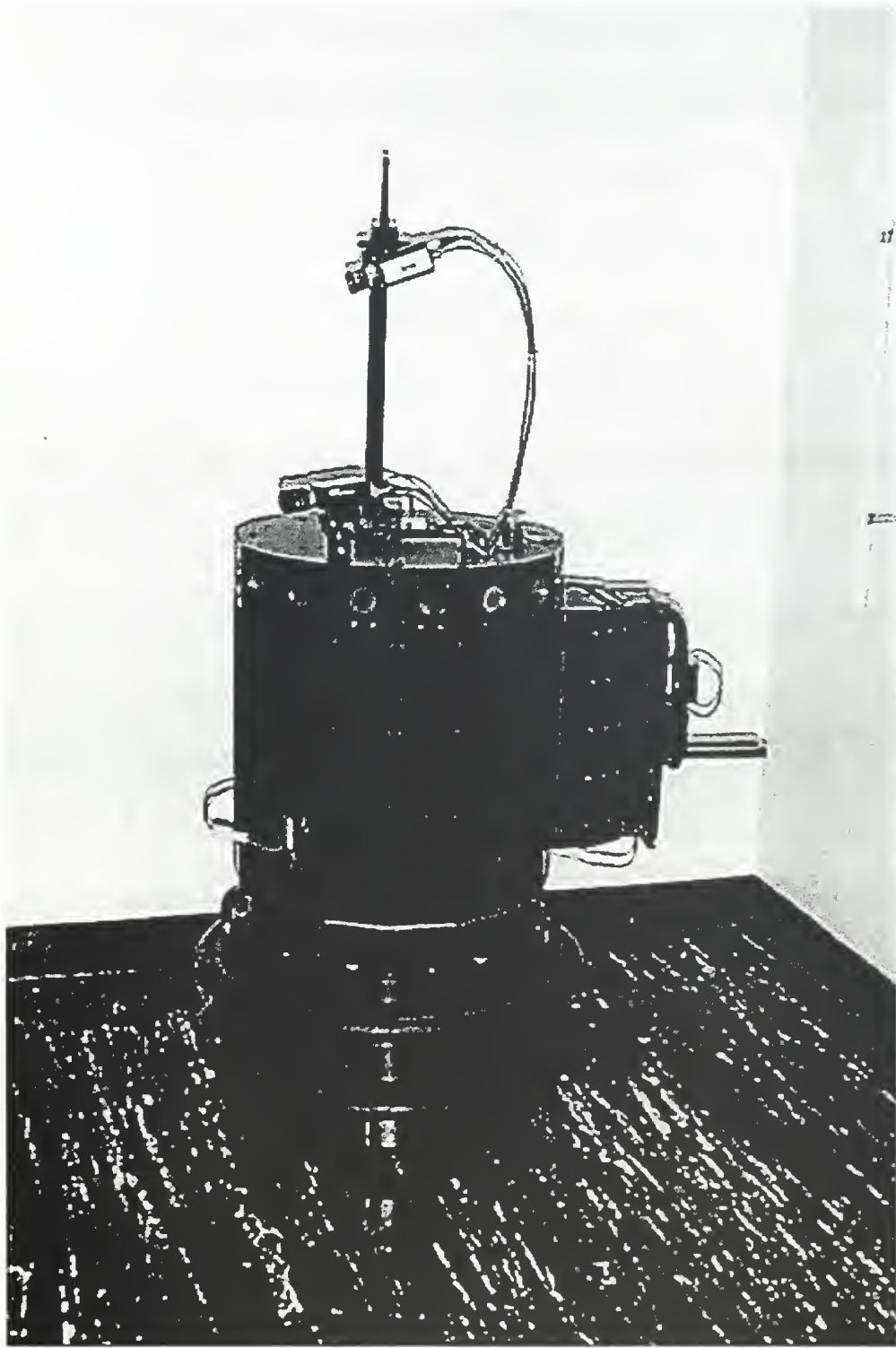


Figure 2. Detailed close-up picture of the NOMAD 200.

The tactile system consists of a bumper ring positioned over 20 independent pressure-sensitive sensors. These simple on-off sensors are interleaved around the bumper ring in order to provide 360° coverage with 18° resolution. [Ref. 4]

The infrared sensors aboard the NOMAD 200 incorporate a 16 channel, reflective intensity based, infrared ranging system that provides 360° of coverage. Each of the 16 sensors is composed of two light emitting diode (LED) emitters and a photodiode detector enclosed in a delrin housing. The range from the sensor to the object(s) is determined by the amount of light from the emitters that is reflected back to the detectors after striking the object(s). The reflectivity of the object greatly affects the reading. Thus the system needs to be calibrated for the environment in which it is to be used. With appropriate calibration, range accuracy is within 5% from 0 to 24 inches from the sensor. [Ref. 5]

The sonar sensors on the robot are composed of a 16 channel, time-of-flight based, sonar ranging system. The system uses standard Polaroid transducers. Each transducer has a beam width of 25°. Range from the sensor to object(s) is determined by the time of flight of the acoustic signal generated by the transducer and reflected back by the object(s). The user has the option to control the firing sequence of the 16 individual sonar sensors mounted about the circumference of the robot. To minimize the potential for sensor interaction, a non-sequential firing sequence is recommended. [Ref. 6]

The laser sensor on the NOMAD 200 is a two-dimensional, triangulation-based laser ranging system. A laser diode is used as the light source and a charged-coupled device (CCD) array camera is used to generate an image. The laser diode produces a

horizontal “plane” of light. The CCD camera is placed vertically above this “plane” and inclined downward. Any object intersecting this plane forms a light stripe on the image generated by the CCD camera. The range to this object is found by determining the position of this light stripe along the scan lines of the camera. This system has an operating range from 12 to 120 inches. [Ref. 7]

3. Previous Work with this Platform

The NOMAD 200 has been and continues to be a very popular research platform at NPS and elsewhere. There exists an extensive body of work involving the NOMAD 200 in several areas in the field of robotics. Some of the more recent work at NPS has involved localization of the robot position in an unknown environment [Ref. 8, 9] and geometric formation and movement in formation of multiple robots in simulation [Ref. 3]. Because NPS only has a single NOMAD 200 (due primarily to the expense of the platform), all work involving multiple robots had to be simulated until very recently. This single robot limitation coupled with the high logistics cost of setting up a very complicated robot platform have been major factors in limiting research performed with real, vice simulated, robots at NPS.

NRL has also done extensive research using the NOMAD 200. Their acquisition of two NOMAD 200 robots has allowed them to conduct more actual research involving multiple robots in addition to simulations. The basis for this thesis is an adaptation of some of their work (described below) in order to form a testbed for actual multiple robot work here at NPS involving less costly platforms.

B. NOMAD SCOUT MOBILE ROBOT

The NOMAD SCOUT is an integrated mobile robot system with ultrasonic and tactile sensors, as well as an odometric system. It uses a multiprocessor, low-level control system that controls the sensing, motion, and communications. At a high level, the SCOUT is controlled either by a laptop, mounted on top, or a remote workstation communicating via radio modem. The SCOUT is code compatible with NOMAD 200 class robots [Ref. 10], which was a very important consideration in its choice as a research platform at NPS. Figure 3 provides a detailed picture of the NOMAD SCOUT.

1. Mechanical Description

The NOMAD SCOUT is a two-degree of freedom (DOF) differential drive robot. The drive is set about the geometric center of the robot, which allows the robot to turn or rotate about its own axis. The NOMAD SCOUT has a maximum speed of one meter per second with a maximum acceleration of two meters per second squared. The robot is .38 meters in diameter and is .34 meters in height. Without batteries, the unit weighs 23 kilograms. [Ref. 11]

2. Sensor Systems

The basic NOMAD SCOUT sensor array includes tactile (bumper) sensors and sonar sensors. In addition to these sensor systems, the NOMAD SCOUT also has an odometric system that tracks the robot's movements. The encoder resolution on this

odometric system is 167 counts/cm for translation and 45 counts/degree for robot rotation.

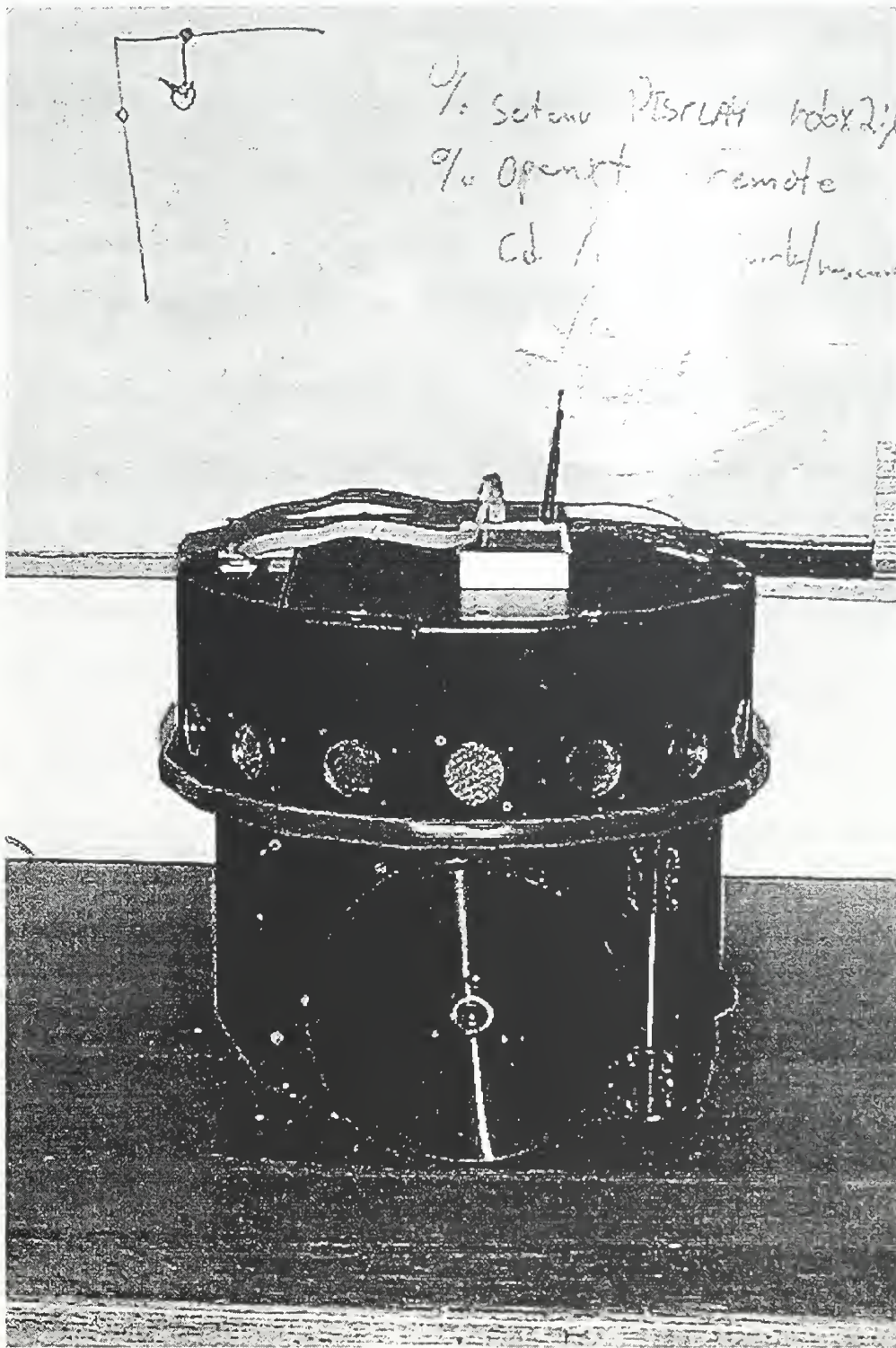


Figure 3. Detailed close-up picture of the NOMAD SCOUT with radio modem.

The tactile system uses a ribbon switch enclosed in an energy absorbing neoprene channel to provide 360-degree coverage. The ultrasonic system uses 16 independent sonar sensors. The effective range of the ultrasonic sensors is 6 to 255 inches. This sonar sensor is basically identical to the one installed in the NOMAD 200 with slight differences due to the smaller diameter of the NOMAD SCOUT. [Ref. 11]

C. COMMUNICATION AND COMPUTATIONAL RESOURCES

No description of the platform would be complete without mention of the software and hardware that allow the robots to operate. A thorough knowledge of the underlying hardware and software is essential in understanding the model being used in this research.

1. Software

The Nomadic Host Development Environment (NHDE) is a full-featured, object-based mobile robot software development package for both the NOMAD 200 and NOMAD SCOUT mobile robots [Ref. 12]. The complete package provides the control and graphics interfaces as well as a very realistic simulation tool for program testing. By using the supplied development package it is much easier to concentrate research on higher level issues of motion planning and control because most of the lower level issues of sensor and motor control are handled by the included software.

The control interface allows for programming the NOMAD 200 or NOMAD SCOUT using a high-level programming language (either C, C++ or Lisp) and linking to a supplied library [Ref. 12]. Built-in to the supplied library are interfaces to the supplied driver software that handle lower level functions such as sensor and motor control. This allows for a higher level of abstraction in the researcher's approach. The graphical user interface and simulator are accessible when the user runs the executable server program, *Nserver* [Ref. 3].

The graphical user interface in the NHDE is based on the OSF/Motif graphics toolkit for the X Window System [Ref. 12]. The graphical interface can display information on up to six robots simultaneously. There are several different windows displayed in the complete graphical user interface. First, there is the world (map) window which gives an overall view of the environment (real or simulated) that the robots are in, as well as the positions of the robots relative to the environment and one another. Secondly, there is a robot window, with one copy per robot, which contains information about each individual robot. This information includes the current command being executed, position and orientation information, and sensor information. Along with each robot window, there are two more windows that give more detailed information about current sensor readings. These two windows are usually used to display a graphical representation of the sonar and infrared returns of each robot's sensors. Detailed information about each robot can be saved as a setup file (*robot.setup*) [Ref. 3]. This includes information about the model of robot (NOMAD 200 or NOMAD SCOUT) being used.

The Nomadic Simulator is a fully functional mobile robot simulator that can accurately model most environments, the robot's motion, and its sensing capabilities. There is a high degree of correlation between the simulated world and the real world. If a program will not run on the simulator it definitely will not work on a real robot. The simulation tool allows the researcher to build a controlled environment in which to develop and debug programs. Using a graphical drawing tool a user can draw a map in the world window to simulate the desired surroundings. This file can be saved as a setup file for the world (*world.setup*). In addition, once a program is running properly on a simulated robot, it can be switched to a real robot via a pull-down menu within the simulator. Once this is done the graphical interface will then begin to display information from the real robot vice the simulated one while commands from the program will control the real robot via the server program (*Nserver*). [Ref. 3]

The NHDE also incorporates several other very convenient features that aid the researcher. There is a record and playback tool that allows for sensor data and/or executed commands to be stored for later analysis, as well as providing for an instant replay capability. This is an invaluable debugging tool. There is also a console available on *Nserver* that allows the user to directly input to the robot any possible command. This is a very handy option for checking the robot's sensors or making small, subtle adjustments in the robots location during experiments. In addition, there is an on-screen, software joystick that allows the user to remotely drive the robot. This is often used to move actual robots around in the real world while simultaneously collecting sensor data.

This allows the researcher to write software that collects and manipulates sensor data without having to also write code to handle the robot's motion.

Figure 4 shows a typical NHDE display from an experiment involving two robots in a simulated environment. Also shown in the figure are many of the features described above such as the global map window, the robot window with its associated sensor windows, the record and playback window, the command console window, and the software joystick window. Also demonstrated in the robot window is another feature available in NHDE. The user has the option to display raw sensor return data or "hits" in the robot window as well as a copy of the global map. This provides a quick visual reference to the researcher indicating whether or not the robot's sensors are functioning properly.

Using *Nserver* in conjunction with the graphical interface and simulation tool is a very convenient way to test and debug software in simulation for subsequent use on a real robot. However, because of the client-server architecture, testing client programs on the real robot via *Nserver* may slow the control and data return rates because *Nserver* acts as a router. Once a program is working properly it can be recompiled to use the control interface library directly without the need for *Nserver* to be running concurrently. This is a very simple process because of the efficient design of the NHDE software.

Each of the application programs for each robot, as well as the *Nserver* when used, can run simultaneously as separate processes under the UNIX operating system. All communications between the host processes that are controlling the robots are

handled as communications between UNIX processes using the TCP/IP protocols and a server-client architecture. This will be described in more detail in Chapter IV.

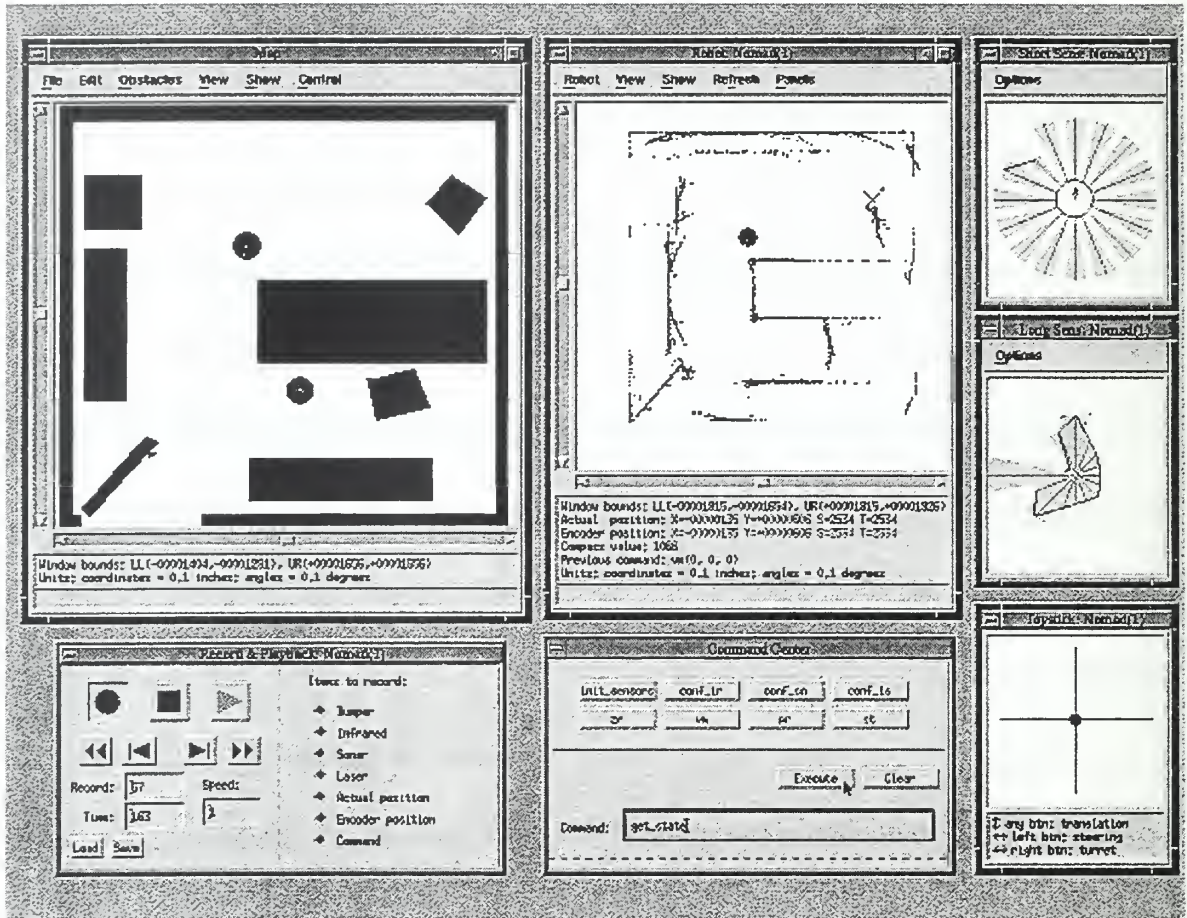


Figure 4. Typical graphical display. (From Ref. [12])

2. Hardware

As mentioned above, each program runs as a separate UNIX process. Whenever practical each process is run on a separate Sun workstation because the frontier-based exploration program is computationally demanding. In addition, running each robot with a separate workstation is more faithful to the system that is being modeled as described in Chapter IV.

Communications from host process to host process are handled as described above and in more detail in Chapter IV. Communications between the host process and the robot it controls are handled via radio Ethernet. Each robot has a 2.4 GHz radio modem. This radio modem is assigned an IP address that the host process uses to route instructions to the robot [Ref. 13]. The radio modem connects to a wireless access point that provides connectivity between the radio modem and the rest of the network [Ref. 14].



III. EVIDENCE GRID BASED MAPPING TECHNIQUES

Over the years many methods have been developed to convert sensor data from robots into useful maps. At times it seems that there are as many different types of robotic mapping techniques as there are robots. Each group of researchers has approached the problem with a slightly different variation or procedure. However, one major method that has proven very successful is called the “grid method.”

A. OVERVIEW OF GEOMETRIC MAPPING TECHNIQUES

A geometric map represents objects according to their geometric relationships. It can be a grid map, or a more abstracted map, such as a line map or a polygon map [Ref. 15]. A geometric map also has the advantage of being easily interpreted by humans trying to match the map with the area that it represents. The key is finding the method that builds the best map.

One of the problems with building a map using simple lines and polygons is that the mapping capability breaks down quickly in a non-simulated environment. These methods depend on interpreting small amounts of sensor return data and mapping points, lines, or surfaces to that data. This can work very well in a simulated environment where obstacles tend to be composed of simple geometric shapes and straight lines, but the real world is not made up of such convenient shapes. Often times such methods map false obstacles or incorrectly shaped obstacles based on extraneous or incorrect sensor data. This is especially a problem when dealing with sensors that return much “noisy” data by

their nature, as do sonar sensors. So these line and polygon mapping techniques are said to be lacking robustness.

The grid technique was developed as a way to overcome many of the problems described above. When using a grid method it is not necessary to make assumptions about the shape or size of an object being mapped. Simply plotting enough sensor return points on a grid forms a recognizable map that can be used by both robots and humans. Once enough points are plotted, edge detection techniques can then be used to pick out walls, obstacles, unexplored areas, and other terrain features. More about edge detection techniques and their uses in mapping will be discussed in Chapter IV.

B. SIMPLE PLOTTING OF SENSOR DATA

Perhaps the most basic of the grid methods is simply plotting the data returned by the robot's sensors and marking areas within the sensors' range as either occupied or unoccupied. This approach has the advantage of simplicity and can produce a reasonably good map in a well-defined simulated environment. However, in a real world environment using only sonar as a sensor this method quickly breaks down unless very tight constraints are set on the range of data used. This was the first mapping technique attempted for this research in conjunction with a single robot. Although this method was later abandoned in favor of a technique better suited for a multiple robot system, it is still useful in depicting some of the complexities of robotic mapping systems.

Figures 5 and 6 illustrate a comparison of simulated and real-world maps constructed by the simple plotting of sonar return data with varying range limitations

imposed on the displayed data. Figure 5(a) is a typical simulated environment used to test various robotic map-making techniques. The environment is a roughly 325 by 275 inch rectangle with several large geometrically shaped obstacles placed within it. Figure 6(a) is a photo of an aisle between two laboratory benches that was used to test map-making methods in a real environment. The aisle has several chairs with metal legs along the robot's projected path as well as open spaces beneath the benches. In both the simulated and real worlds the robot is remotely moved through the environment via the software joystick described above.

At the same time the user remotely moves the robot, another process is running which collects the sonar return data and the robot position and orientation (*pose*) data and writes it to a data file. Pose data is very important in converting the sonar returns for a given robot position and orientation into data that can be mapped onto a common coordinate system. After the data were collected, a MATLAB routine read the data file, transformed the sonar return and pose data, and plotted the resulting map. Along with the sonar return data the robot's path in the simulated or real world is also plotted as a dotted line in the resulting map. In this case the map was generated after maneuvering the robot, but *Nserver* also allows for the raw sensor returns to be plotted in real time within the robot window.

In Figures 5(b) and 6(b) the reliable sonar range is set to 255 inches (the maximum rated reliable range according to the manufacturer's specifications). Thus, the mapping program plots all sonar return data that is below 255 inches. A return of 255 inches is regarded as open space and not plotted. In the simulated world this produces a relatively

good map with some noise at corners and other line intersections. In the real world there is much noise and what appear to be many extraneous returns. This noise and the apparent false returns will be discussed in more detail in Chapter IV.

In Figures 5(c-e) and 6(c-e) the reliable sonar range is steadily reduced and a larger percentage of the raw sonar returns eliminated and not plotted. Correspondingly, as the outlying returns are discarded, the data that is plotted produces clearer and less noisy maps. Unfortunately, as can be seen very well in Figure 5(e), dropping the longer returns in the larger simulated environment resulted in the robot path being too distant from several obstacle walls, preventing them from being mapped. This illustrates the tradeoff between reducing the reliable sonar return range in order to get quality data, and forcing the robot to travel further in order to close in on all mappable objects in the environment. More about this tradeoff will be discussed in greater detail in Chapter V.

Plotting every sensor return does not prove to be the best method of constructing a useable map. The same simplicity that makes it so easy to implement also proves to be its downfall in real world situations. It is possible to fuse maps together with this method by converting all returns to a common coordinate system, but the main problem is that all data is given the same amount of validity. What is needed is a method to weigh, or measure, the “goodness” of sensor data from multiple sensors at multiple positions and build a map accordingly.

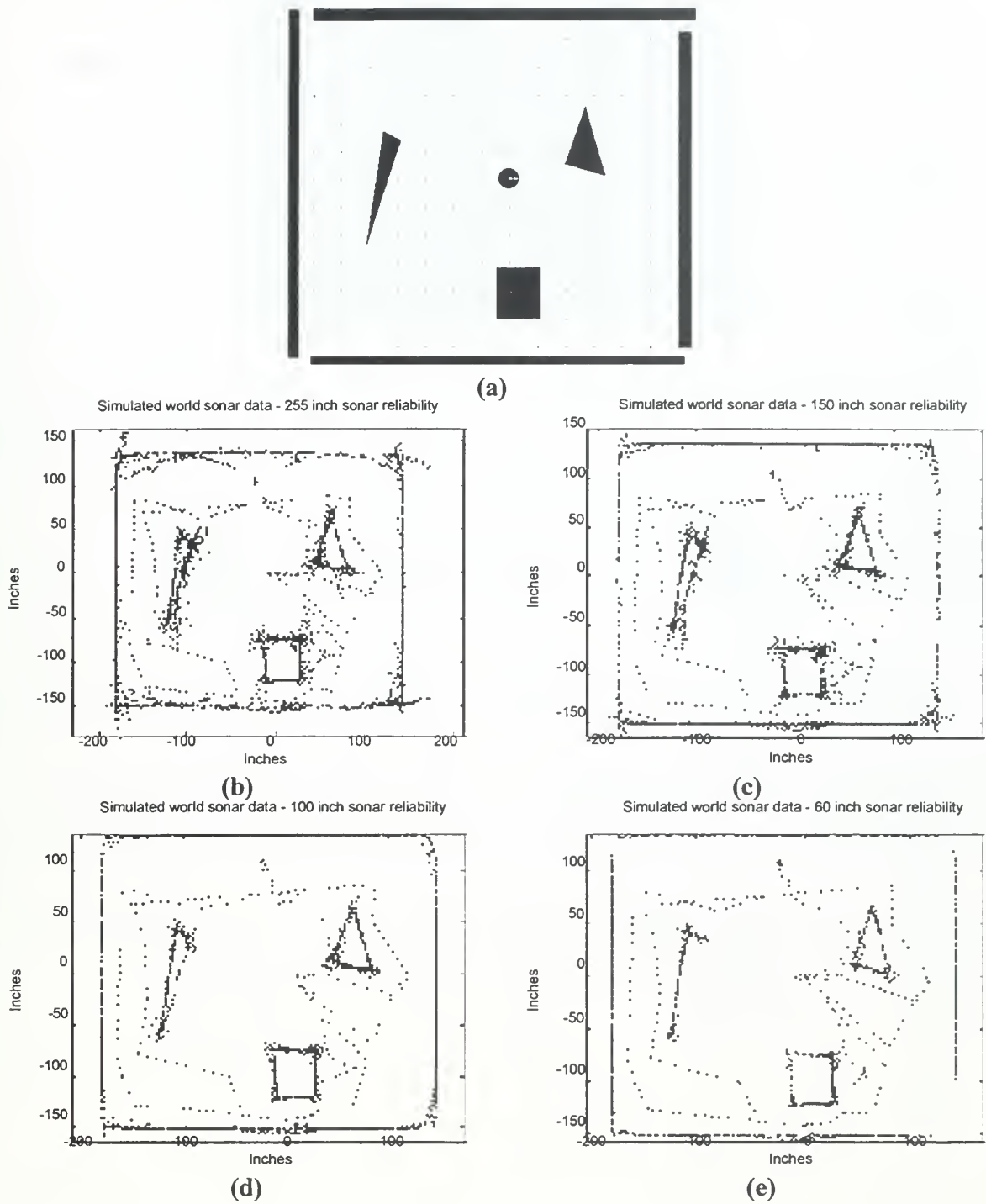
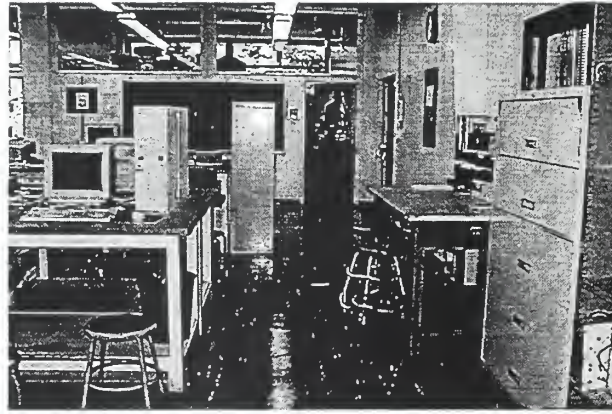
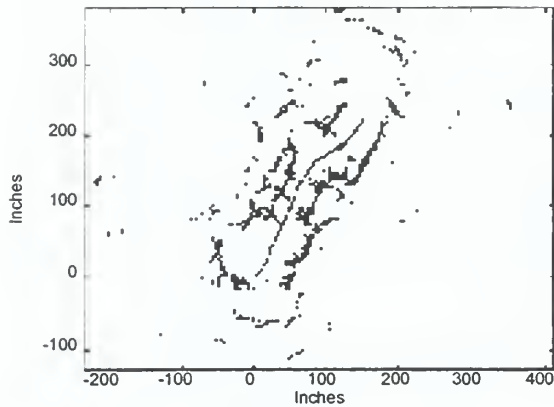


Figure 5. Illustration of simulated environment and the resulting sonar maps formed by maneuvering the simulated robot throughout it, collecting sonar range data, and plotting subsets of that range data based on estimated reliability.



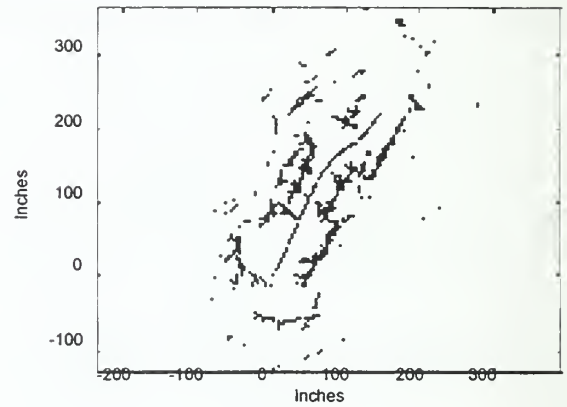
(a)

Real world sonar data - 255 inch sonar reliability



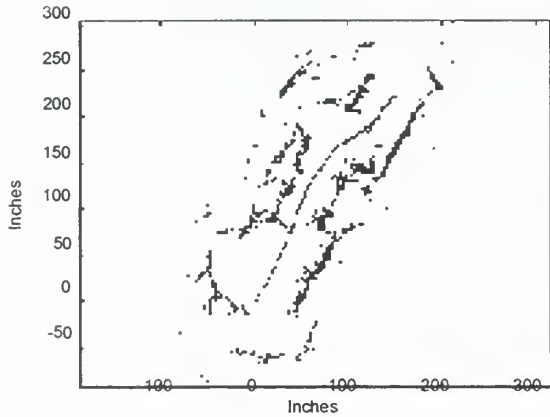
(b)

Real world sonar data - 150 inch sonar reliability



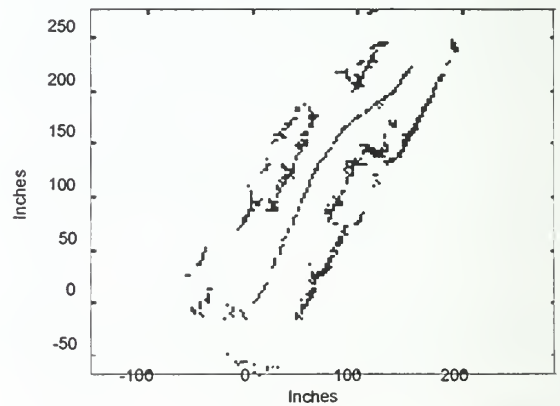
(c)

Real world sonar data - 100 inch sonar reliability



(d)

Real world sonar data - 60 inch sonar reliability



(e)

Figure 6. Illustration of real world environment and the resulting sonar maps formed by maneuvering the actual robot throughout it, collecting sonar range data, and plotting subsets of that range data based on estimated reliability.

C. THE EVIDENCE GRID METHOD

The evidence grid method was developed as a technique to create high resolution maps from wide-angle sonar. This approach allows range measurements from multiple points of view to be systematically integrated into a common map. The integration technique allows for multiple readings of an area to either reinforce or refute one another as to the whether or not the area is occupied. As more sensor data is added the definition of the map improves. [Ref. 16]

In the evidence grid method, the area to be mapped is divided into a grid with $M \times N$ cells. In each of these cells is stored a set of information regarding the best estimate as to what that cell contains. This “evidence” can be many different things, such as the surface orientation or color of whatever is in the cell, but for mapping perhaps the most useful information is occupancy information concerning the cell [Ref. 17]. Early versions of this method [Ref. 16, 18] stored this occupancy information as a two part record with a status of either *unknown*, *empty*, or *occupied* and an associated certainty factor of either 0, -1 to 0, or 0 to 1 respectively. Early versions also used ad hoc formulas to combine this information about each cell into a useable map.

Later implementations [Ref. 17, 19, 20] eliminated the two part occupancy record and replaced it with a single value representing the probability that the cell is occupied. This technique also allowed for a better method of combining and integrating sensor data using a variation of Bayes theorem. In this representation, an unknown or unexplored cell would have an occupancy probability of 0.5. As more sensor data becomes available this

probability changes accordingly. The details of how this sensor data is integrated together are the topic of the next section.

D. FUSING SENSOR DATA USING AN EVIDENCE GRID

The major advantages of the evidence grid method over previous methods are the ability to weigh or measure the “goodness” of the sensor data and the ability to fuse this data in a simple, yet effective, manner. The best way to demonstrate how the sensor data is fused is to first present a graphical representation and then go more in depth into the mathematics behind it.

1. Graphical Presentation

Figure 7 shows a sequence of images simulating the fusion of sonar sensor data from two different points. In this sequence, the circles labeled A and B represent locations at which a sonar sensor sends out a pulse and receives a return. Points A and B could be different sensors on the same robot, the same sensor on a single robot at a different time, location and/or orientation, or two different sensors on two separate robots. The advantage of this sensor fusion method is that for all practical purposes, exactly what they are does not matter. The only thing that matters is that the readings be relatively independent of one another. For the purposes of this explanation, they will be referred to as sensor A and sensor B . The background grid will represent the evidence grid that will be developed in order to map the region. As per most recent implementations of

the evidence grid model it will be assumed that all the cells on the grid will be initialized to an initial occupancy probability of 0.5.

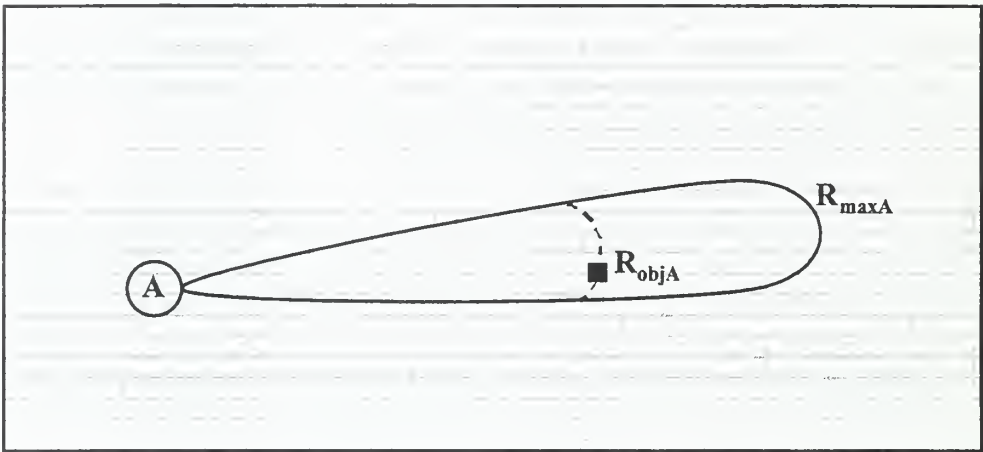
In Figure 7(a) the relative geometric locations of A and B are shown, along with some object in the distance. Figure 7(b) shows a two-dimensional “slice” of a three-dimensional sonar cone emanating from A . R_{maxA} is the maximum effective range of sensor A . R_{objA} is the range at which the object is detected some distance away from A . Because of the wide-angle nature of the sonar sensor the object is known to be only somewhere on a certain surface [Ref. 20]. In this case the dashed line represents the edge of the circular “slice” of the sonar cone along which the object might lie. So at this point it is known that an object lies somewhere within a constrained region.

The shape of that region and its distance from A are also known, but there is not enough information at this point to make an assumption about exactly where in that region the obstacle exists. Under the evidence grid model the occupancy probabilities of the cells along that entire region would be increased. In the two-dimensional case this would mean all the cells along the dashed line. The amount of increase might vary depending on several factors such as distance from target, angle from sensor, or other measures of sensor data quality, but the main point is that the occupancy probabilities along the assumed obstacle location would be increased relative to the surrounding cells.

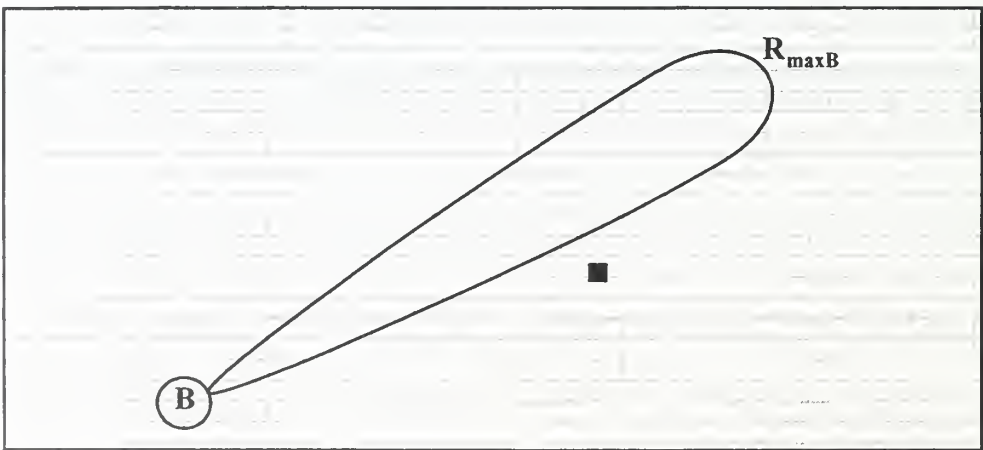
Figure 7(c) shows the two-dimensional representation of the sonar cone emanating from B . Again, B may be the same sensor as A at different time, location, and/or orientation or a separate sensor on the same or a different robot. In this case B does not sense the obstacle within the region it is observing.



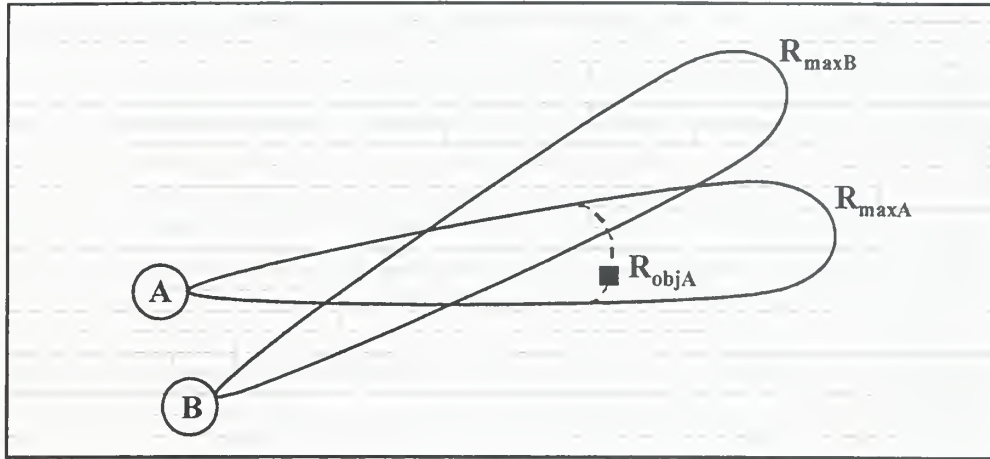
(a)



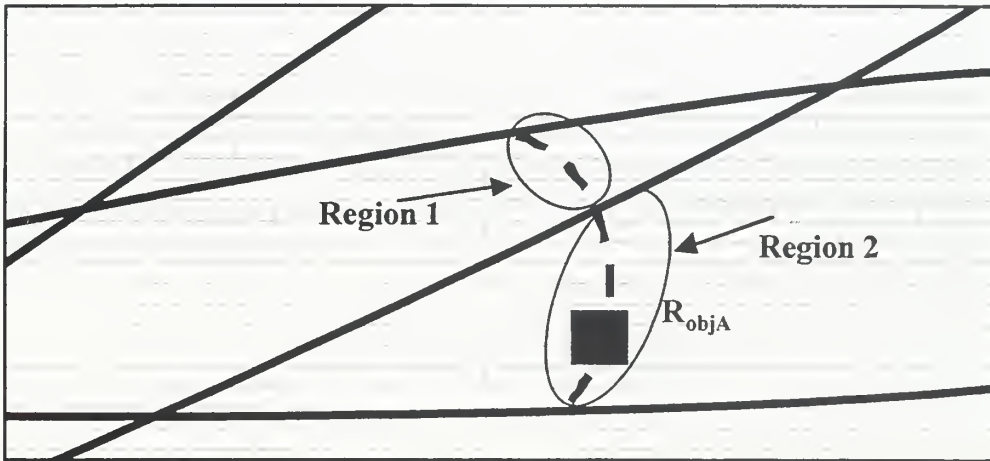
(b)



(c)



(d)



(e)

Figure 7. Example of fusion of sonar return data from two geographically different sonar sensors.

Figure 7(d) displays both the sensor readings from *A* and *B* simultaneously. In this case part of the sensor reading from *B* overlaps some of the region of the sensor reading from *A* where the cells had had their occupancy probability raised relative to the surrounding cells. However, the data from sensor *B* now provides additional information

concerning portions of this area and that information can be used to adjust the occupancy probabilities in that region accordingly.

Figure 7(e) shows an enlarged view of the area where the sensor readings from A and B intersect. In the evidence grid model the information from A and B would be combined in such a way as to lower the occupancy probabilities of the cells within the circle marked *Region 1* that are in view from both A and B . At first it would seem logical to also increase the occupancy probabilities of those cells within the circle marked *Region 2* as well. However, because the evidence grid model used considers each sensor reading to be relatively independent of every other sensor reading, the reading from B cannot be used to adjust the occupancy probabilities of the cells in *Region 2* because those cells are not in view of B .

Depending on the detailed specifics of the model chosen, the occupancy probabilities of the cells in *Region 1* might still be higher than their immediate neighbors that were always considered empty, but they would always be lower than those of the cells in *Region 2*. So even though the cells in *Region 2* are not directly changed through this process, their occupancy values are now the local maxima for the overall area within the large evidence grid shown in the figure.

Figure 7 illustrates the evidence grid method on a small scale. Now imagine it on a much larger scale with multiple sensors on multiple platforms and many hundreds to thousands of relatively independent sensor readings from a multitude of ranges and orientations. It is by combining all of these together that a map is created using the evidence grid method. The mathematical details of this process are described below.

2. Mathematical Presentation

Perhaps the clearest and most concise mathematical description of the evidence grid method of combining sensor data can be found in [Ref. 17]. What follows in this section is a condensed version of that work presented here for clarity and completeness.

Let $p(A|B)$ represent the best estimate of the likelihood of situation A given that information B has been received. A and B mean either “a certain region of space is occupied,” (written o), “a certain region of space is unoccupied”, (written \bar{o}), or they represent a sensor reading. By definition, $p(A|B) = p(A \cap B) / p(B)$. The quantity $p(A)$ represents the estimate of A given no new information. The alternative to situation A is written \bar{A} , (read as “not A ”).

For the two occupancy cases of a cell, o (the cell is occupied) and \bar{o} (the cell is empty), and new information M (derived from a sensor measurement), the above definition creates the equation:

$$\frac{p(o|M)}{p(\bar{o}|M)} = \frac{p(M|o)}{p(M|\bar{o})} \frac{p(o)}{p(\bar{o})} \quad (1)$$

Now this can be rewritten as:

$$\frac{p(M|o)}{p(M|\bar{o})} = \frac{p(\bar{o})}{p(o)} \frac{p(o|M)}{p(\bar{o}|M)} \quad (1a)$$

Now suppose that there exists some information, M_1 , that has already been processed into a map, i.e. $p(o|M_1)$ already exists and it is desired to integrate some new measurement, M_2 , to find $p(o|M_1 \cap M_2)$. In order to make the analysis tractable it is assumed that the new measurement is independent from all previous information. This

may not be completely true, but for the purposes of constructing a map from many sensor inputs it simplifies the problem immensely. However, it is not implied that $p(M_1 \cap M_2) = p(M_1)p(M_2)$, since if M_1 indicates that the cell is occupied then it is hoped that M_2 would be more likely to indicate the same thing. Instead, what is meant is that, given that the cell is occupied, the probability of getting reading M_1 is independent of getting M_2 , and similarly for the cell being occupied:

$$p(M_1 \cap M_2 | o) = p(M_1 | o)p(M_2 | o) \quad (2)$$

$$p(M_1 \cap M_2 | \bar{o}) = p(M_1 | \bar{o})p(M_2 | \bar{o}) \quad (3)$$

Another way to look at this assumption is that it is only assumed that the sensor's errors are independent from one reading to the next. This is especially true of noisy sonar sensor data, in which the errors vary greatly from one reading to another from the same sensor due to changes in range, orientation, etc. Combining this assumption with a single application of Equation 1a, results in:

$$\frac{p(o | M_1 \cap M_2)}{p(\bar{o} | M_1 \cap M_2)} = \frac{p(o | M_1)p(M_2 | o)}{p(\bar{o} | M_1)p(M_2 | \bar{o})} = \frac{p(o | M_1)p(o | M_2)p(\bar{o})}{p(\bar{o} | M_1)p(\bar{o} | M_2)p(o)} \quad (4)$$

We generally assume that the a priori probability of a cell being occupied is 0.5, i.e., $p(o)=p(\bar{o})=0.5$, so that the last factor in Equation 4 cancels out. When the information M_2 is a sensor reading, the value $p(M_2 | o)/p(M_2 | \bar{o})$, for all cells and all possible readings, is called the sensor model. In other words, the sensor model is a function which attaches a number, $(p(M_2 | o)/p(M_2 | \bar{o}))$, to every combination of sensor reading and cell location, relative to the sensor. This assumes that the sensor is isotropic in its world position and pointing direction. In general, the sensor model is a

function of the sensor reading, the location and orientation of the sensor, and which cell is being updated. Also, while the sensor reading M_2 may represent a continuous number indicating distance from the sensor, in general, each time the sensor is polled it will return an element from some set and M_2 will range over all elements of that set.

The sensor model is usually independent of the current map and can be stored in tables. A further speed up of the process can be achieved if the logarithm of the above probability ratio is used. In this case the model uses:

$$\log \frac{p(o | M_1 \cap M_2)}{p(\bar{o} | M_1 \cap M_2)} = \log \frac{p(o | M_1)}{p(\bar{o} | M_1)} + \log \frac{p(o | M_2)}{p(\bar{o} | M_2)} \quad (5)$$

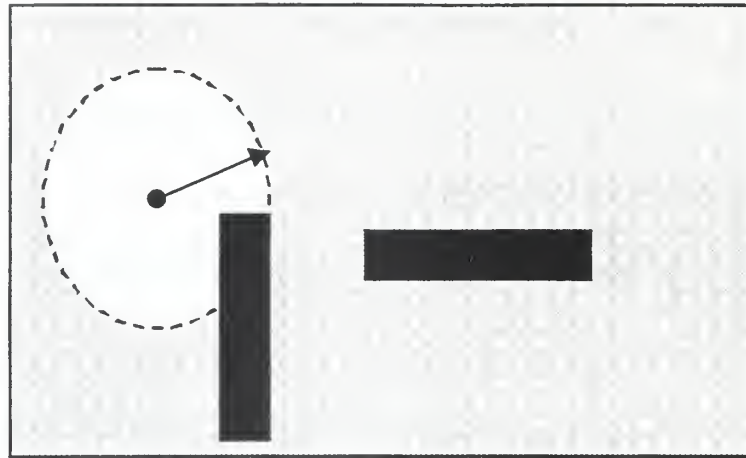
In the logarithmic method the combining formula is changed from a multiplication to a simple addition. In this case the logarithmic result itself can be considered as weight of evidence of cell occupancy. Therefore, the need for only a single addition per cell allows for very rapid updating of the evidence grid map based on the newly acquired sensor data.

IV. FRONTIER-BASED EXPLORATION

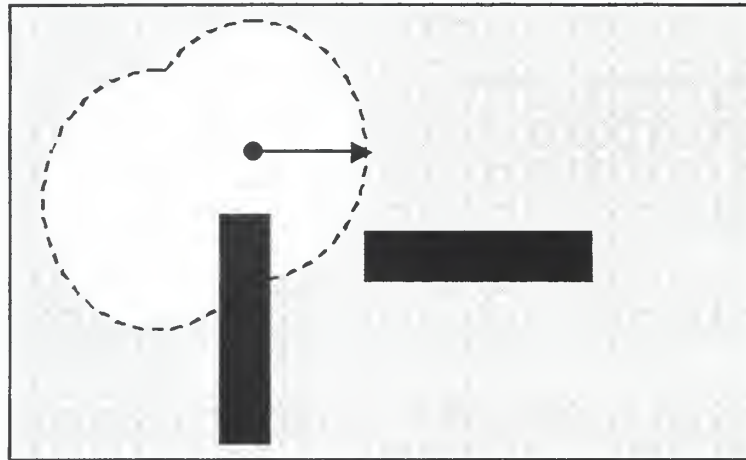
One of the goals of a robotic-based reconnaissance system is to reduce the amount of manpower required to reconnoiter an area. Any system worth building should be able to explore at least a limited area autonomously and in a fairly efficient manner. This means that the robots will have to be able to make use of the maps they will build as they move through their environment. Chapter III already discussed in great detail the way those maps might be represented, now it is time to discuss how a robot would use them to explore and map an area on its own.

A. DEFINITION

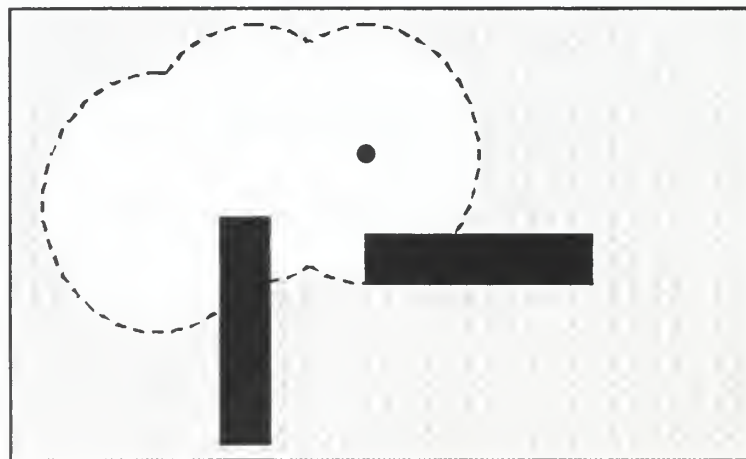
A robot exploring a new area will initially know nothing about that area except what it can detect in its immediate area with its own sensors. The limits of its sensors will form a boundary between known, explored space and unknown, unexplored space. Such a boundary is called a frontier. Within this boundary it is assumed that all obstacles are known and mapped. Thus, further exploration within this boundary would be futile. In order to maximize exploration in the least amount of time, the robot should move to the boundary between explored and unexplored space as soon as possible and use its sensors to expand the explored region. At the same time the act of expanding this known region will in turn create new boundaries or frontiers for the robot to explore. This is the central idea behind frontier-based exploration. This process is illustrated in Figure 8. [Ref. 22]



(a)



(b)



(c)

Figure 8. Example of frontier-based exploration. Robot begins by scanning immediate area, incorporates result into its map noting frontiers yet to be explored, moves to a frontier, and repeats the process.

Figure 8(a) shows a robot at startup in some unknown environment. The black circle represents the robot. The two large black rectangles represent obstacles in the area to be explored. The white space surrounding the robot is the area it can directly detect with its own sensors. The gray background represents the unexplored regions and the black dashed line represents the boundary between the known and unknown space.

In Figure 8(a) the robot can detect the top edge of the first obstacle, but the obstacle blocks its view what may be behind the obstacle. Accordingly, the robot chooses a frontier and proceeds to that frontier in order to continue the process of exploration and map building. Figure 8(b) shows the robot in its new position now able to see behind the first obstacle. After scanning in this position the robot moves on to the position shown in Figure 8(c) where it can now detect the second obstacle. This process could continue indefinitely as long as there are unexplored frontiers for the robot to explore.

B. FRONTIER DETECTION

Before a robot can decide on a frontier towards which to proceed in order to continue exploration, it must first decide where the frontiers are within the region it has already explored and mapped. In order to detect these frontiers a process similar to edge detection and region extraction in computer vision (also known as machine vision) is used to find the boundary between mapped open space and unmapped unknown space [Ref. 23].

Over the years many techniques have been developed in the area of computer vision to extract information from photographic images based on the pattern of changes in brightness in the picture [Ref 24]. Most of these techniques involve decomposing the image into a set of pixels, much like a grid. Each cell in the grid is given a value based on the brightness of the pixel that the cell represents from the original image. This grid is then searched for patterns that may indicate edges or patterns of interest.

There are a variety of methods for picking out the patterns in the image depending on the information that is desired. Some techniques involve the use of a set of “masks” composed of a small (on the order of 3 X 3 or 4 X 4) pattern of cells of varying values that are successively laid across the original image. As the mask is moved across the image the cells of the mask are convolved with the cells of the image beneath the mask and the resulting matrix indicated the presence of edges in that portion of the original image. Other methods rely on simple histograms of the brightness values of the cells in the original image and attempt to use curve-fitting techniques to pick out edges of objects in the real world.

Regardless of the methods used, these same types of techniques can be applied to detecting boundaries in frontier-based exploration. The same underlying grid format will be used as in computer vision, but in the case of frontier detection the values in the cells do not represent the brightness of a pixel. Rather, they represent the occupancy probability of a cell in the area the robot is exploring.

In general each cell in the area being examined for frontiers will be placed into one of three categories [Ref. 23]:

- **open:** when the current occupancy probability of the cell is less than the prior probability
- **unknown:** when the current occupancy probability of the cell is the same as the prior probability
- **occupied:** when the current occupancy probability of the cell is greater than the prior probability

A short explanation about the term “prior probability” is needed. When the evidence grid is first created it is necessary to initialize the cells in the grid to some value. Since at creation nothing in the grid has been explored it is logical to initialize all the cells to an occupancy probability value representing unknown, unexplored areas. All the implementations of frontier-based exploration discussed here [Ref. 22, 23, 25] initially set the cells’ values to 0.5. When the frontier-detection process is first done it is this initial (prior) occupancy probability to which the current occupancy probability will be compared.

After a robot starts up or moves to new frontier it will make a sensor scan of the surrounding area. Based on the information returned from its sensors it will update the occupancy probability value of any cell with direct range of its sensors. The robot will then use this updated information to perform frontier detection. Any open cell adjacent to an unknown cell will be labeled as a frontier edge cell. Adjacent edge cells are then grouped into frontier regions. Any frontier region above a certain minimum size (say

roughly the size of the robot) will be considered an accessible frontier and marked as such.
[Ref. 23]

C. NAVIGATION

Once the robot has scanned an area and updated all cells of the evidence grid within range, it must now safely and efficiently navigate to a new frontier in order to continue exploration and map building.

1. Route Planning

Navigation to a new frontier should involve a path that is completely within known space, therefore, all obstacles in that space should be known. Route planning involves choosing the best path (based on some criterion such as length of path, nearest approach to obstacle, etc.) through the known space to the frontier to be explored. This path will be based on the latest update of information concerning explored space.

There are various algorithms such as depth-first, breadth-first, and A* search routines [Ref. 26] that attempt to search through a known map for safe and efficient navigation paths. However, a problem can arise if an obstacle (for example, another robot) moves into the chosen path since the last time information about the known space was updated. This may lead to the path the robot chooses to move to a new frontier being blocked. In that case, in order to avoid collision with the new obstacle and continue

navigating to the chosen frontier requires that the robot have some means of reactive avoidance.

2. Reactive Obstacle Avoidance

Reactive obstacle avoidance entails some method of detecting and reacting to mobile obstacles that appear in the robot's path that were not in the then-current map used by the route planning routine to plot a safe path for the robot. Mobile obstacles may include humans, other robots, or any of a number of other unpredictable phenomena that may exist in the robot's world. For the most part, reactive obstacle avoidance involves the use of relatively short-range sensors (IR, contact, etc.) or long-range sensors (sonar, vision, etc.) scanning in the area immediately surround the robot as it moves.

One important note about sensors and reactive obstacle avoidance is that the required scanning rate of the obstacle avoidance sensors is closely related to the expected travel rate of the robot and the anticipated characteristics of the area in which it is traveling. Obviously a quickly moving robot in an area where new obstacles appear frequently will need to scan the local area around it much more frequently than a slow moving robot in a well known, stable area.

There are several different actions that a robot might take upon detecting a new obstacle along its planned path. One common method is to use some sort of very low-level navigation routine that simply finds a path around the new obstacle and gets the robot back on the previous planned path as quickly as possible. This eliminates the need to call on the slower full route-planning algorithm. For small obstacles in the robot's

planned path this is usually the method used. However, a problem can arise with this method when the new obstacle is so large that the low-level process cannot easily find a way for the robot to get around it. Normally, in this case the robot would stop and the full route-planning algorithm would be called on to find a new path to the robot's destination based on the new information about obstacles in the robot's path.

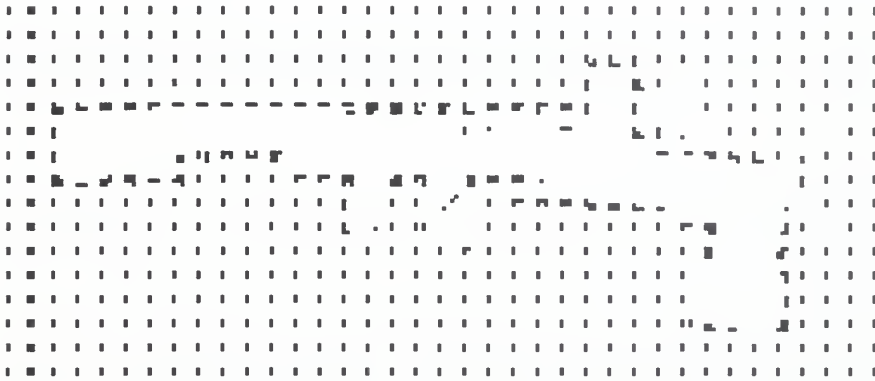
3. Localization Error

Every time the robot moves there is some slippage of the wheels that will cause the odometric encoders to incorrectly record the distance and direction the robot has traveled. Eventually, without some means of correction, the localization errors become so great that mapping and navigation become impossible. Methods of minimizing localization errors in mobile robots are the topic of much research [Ref. 20, 22, 27].

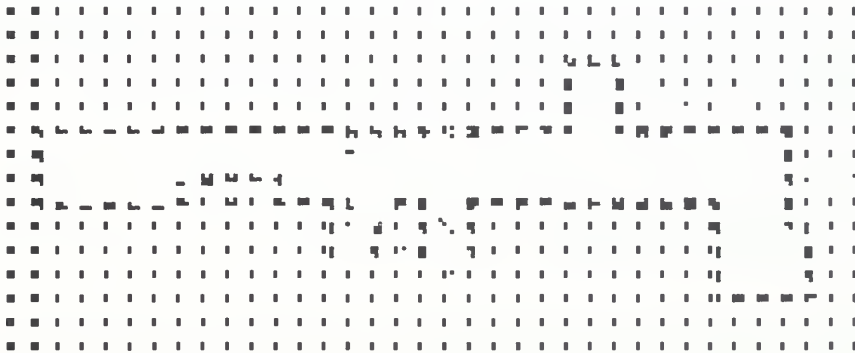
Figure 9 demonstrates the effects of robotic mapping with and without localization error correction methods while mapping a long, obstacle filled hallway. Figure 9(a) shows an evidence grid representation of the area to be mapped. Figure 9(b) shows a map developed by a frontier-based exploration system without the aid of any localization error minimization techniques. As the robot's coordinates become uncertain the sensor return data begins to "drift." Figure 9(c) shows the map which was developed using a continuous localization process that seeks to correct for dead reckoning errors that accumulate as the robot moves throughout the area to be explored. [Ref. 22]



(a)



(b)



(c)

Figure 9. Example of localization error and correction. Shown from top to bottom are the ground truth evidence grid, the map constructed without localization, and the map constructed with localization. [From Ref. 22]

D. NRL IMPLEMENTATION ON SINGLE NOMAD 200 ROBOT

The full implementation of the frontier-based exploration code (for both single and two robot systems) as developed at NRL consists of over 60 separate C and C++ routines that are then compiled into a single process. Many of these routines handle the various ‘housekeeping’ functions of any large, complicated program (i.e. display, input/output, etc.) and do not bear directly on this thesis. Relevant routines and their use will be discussed below and portions of the code from these routines will be reproduced in the appendices.

The latest version of the full code (as well as all previous versions) is available from Brian Yamauchi (yamauchi@aic.nrl.navy.mil) at NRL’s Navy Center for Applied Research in Artificial Intelligence (NCARAI). The NPS modified version of the code is available from Xiaoping Yun (yun@ece.nps.navy.mil) at the NPS Department of Electrical and Computer Engineering (ECE).

1. System Overview

There are a few major processes in the NRL code that bear directly on single robot, frontier-based exploration. The three key parts of their single-robot system that are relevant here are: the use of laser-limited sonar (LLS) for sensor scanning at new frontiers, the exploration routine used for the detection of new frontiers and the subsequent movement to and scanning of those frontiers, and the integration of the new scan with the robot’s current map.

2. Laser-Limited Sonar (LLS)

There has been much study of the characteristics of the simple type of Polaroid sonar units found on the NOMAD 200, the NOMAD SCOUT, and many other research and commercial robots [Ref. 28]. The low cost, low weight, and low power consumption of these types of sonars has made them very popular among robot builders and designers, however, they do have their drawbacks. As noted in Chapter III sonar returns in the real world environment tend to include much noise and many extraneous or false returns. Many of these questionable sonar returns are caused by a phenomenon known as specular reflection.

Specular reflection occurs when a sonar pulse hits a flat surface at an oblique angle and reflects away from the sensor instead of directly back to the sonar detector [Ref. 25]. When this happens there may be several different results depending upon the circumstances. If the sonar pulse reflected off of the oblique surface encounters a flat reflective surface soon after, then the detector may still get a return, but the first object that the sonar pulse struck will appear to be further away than it is in actuality. If the sonar pulse continues on to the sonar's maximum range without striking another object, then the nearby object may not be detected at all, but instead it will appear that there is a large open space surrounded by an unknown area.

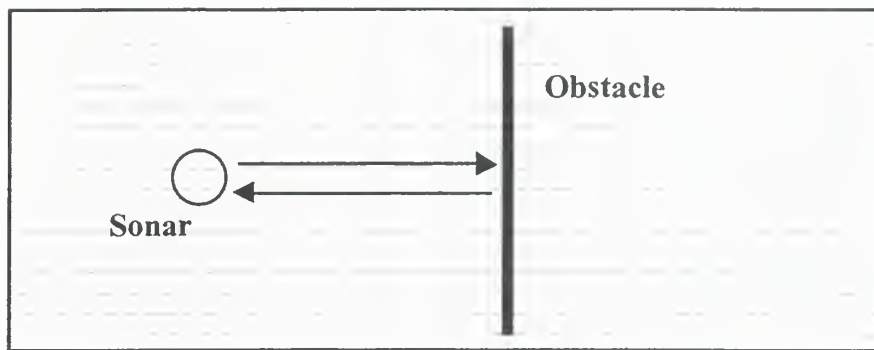
In reality, the possibility of not detecting a nearby obstacle is not as great as it first appears. With many sonars onboard the robot firing from several different angles, there is usually not much problem with getting some measurable level of sonar from

nearby objects and detecting them even if there are facing obliquely to some sensors.

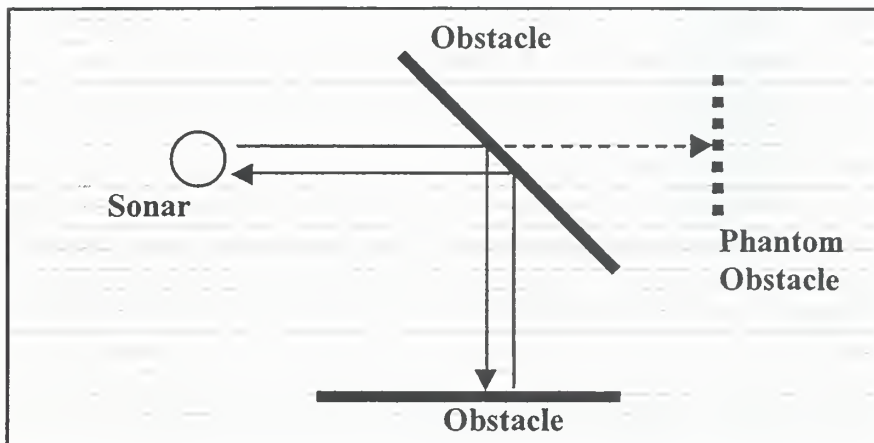
However, the problem of detecting “phantom” obstacles and false open spaces is still a problem that needs to be considered. Figure 10 provides an example of a normal sonar return and two of the possible results of a specularly reflected return.

Figure 10(a) illustrates a normal sonar return with the sonar pulse represented by the ray emanating from the sonar, striking the nearby obstacle, and a measurable amount of energy returning to the detector. The head-on encounter of the sonar pulse with the flat face of the obstacle toward the sonar provides for a clear return path. In Figure 10(b), however, the oblique angle of the nearby obstacle reflects the sonar pulse away where it encounters the second obstacle. If a measurable amount of energy is returned from the second obstacle, then it may appear to the sensor that there is a “phantom” obstacle at the point shown in the figure. There may be a partial sonar return from the first obstacle as well, which could further confuse the sensor about the exact nature of nearby obstacles.

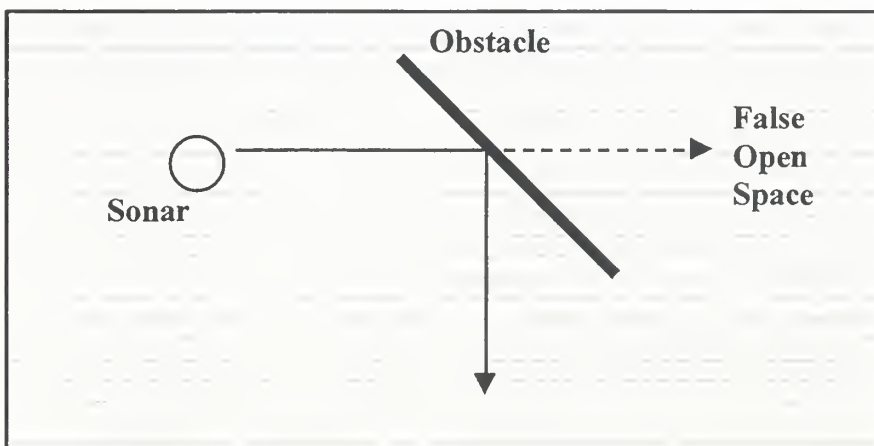
Figure 10(c) demonstrates what may happen if there is no second obstacle within the maximum range of the sonar sensor after the pulse has been reflected from the first nearby obstacle. The sensor would receive either a very weak or non-existent return from the nearby object. If no return is received then it will appear that a large open space exists in the area shown, when in fact there is really no information known about that area at all. Since this false open region would most likely be surrounded by unknown space it would also have the effect of creating false frontiers for the robot to explore.



(a)



(b)



(c)

Figure 10. Examples of a normal sonar return, a specularly reflected sonar return that creates a phantom obstacle, and a specularly reflected pulse that generates a false open space. (After Ref. [25])

In addition to the sonar sensors, the NOMAD 200 has a laser based range finding systems that does not suffer from these same type of specular errors. The researchers at NRL have taken advantage of this and created a technique known as laser-limited sonar (LLS). By using the readings from the laser rangefinder in combination with the readings from the sonar it is possible to eliminate most many false readings from walls and other large obstacles that cause the majority of specular reflections. If the laser returns a range to obstacle less than the sonar, then the evidence grid is updated as if the sonar had given the range indicated by the laser. [Ref. 23]

The laser cannot be used exclusively for mapping because the laser rangefinder currently available on the NOMAD 200 only operates in a two-dimensional plane, while the sonar senses obstacles within a three-dimensional cone radiating out from the robot. Objects above or below the plane of the laser will be missed by the laser, but detected by the sonar. Figure 11 provides an example of how this might happen. In this figure the laser plane is above the obstacle and thus the laser rangefinding system never detects it, but the sonar cone emanating from sonar sensor does intersect the obstacle. This is a case of using two different sensor types that compliment one another. A three-dimensional rangefinder would be an alternative that would combine the best aspects of both sensors, but presently these type of systems are too large, expensive, and power consuming to be commonly used on mobile robots. [Ref. 23]

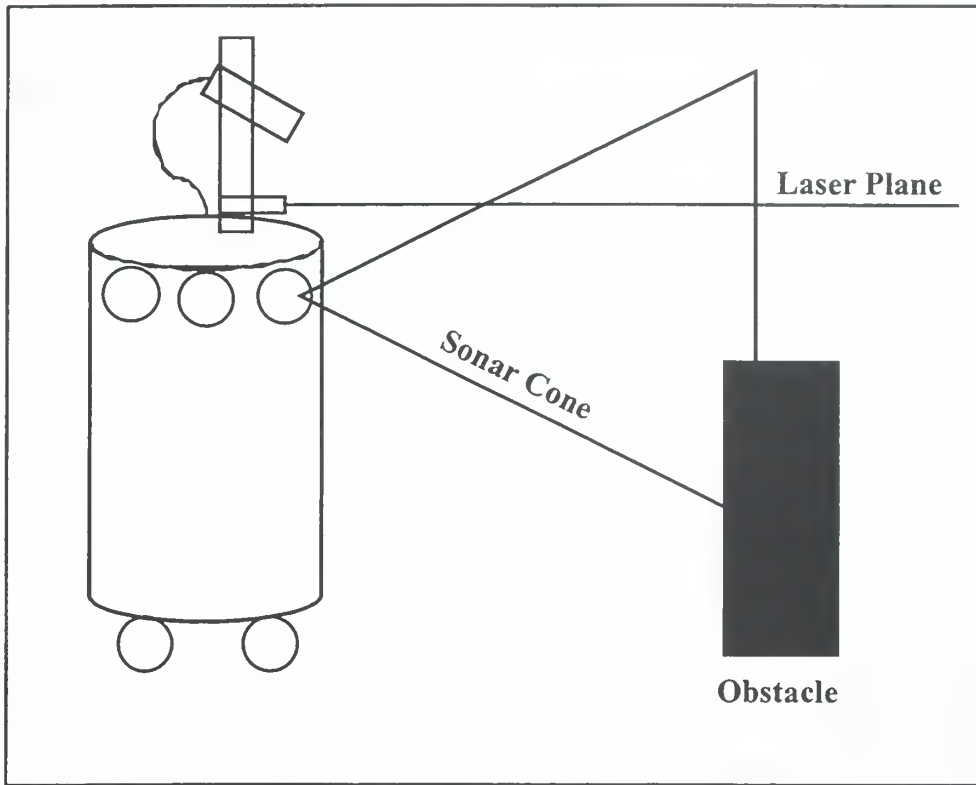


Figure 11. Example of two-dimensional laser rangefinder failing to detect an obstacle that is within the detection cone of the sonar sensor. (After Ref. [25])

3. Frontier-Based Exploration Routine

The heart of the frontier-based exploration code is in the file *agent.cc*. It is in this operation that the frontier-detection, navigation, and exploration behaviors are described. This procedure also controls the laser-limited sonar scanning technique mentioned above and also takes care of integrating the newest scan with the current map via the method described below. The process begins by completing an initial sensor scan of the area upon startup and using the data obtained to construct an initial evidence grid map. After the initial map is created, a frontier detection subroutine is called to find and note nearby frontiers for further exploration. Once the frontier detection is complete the exploration

and navigation subroutines are called to choose the robot's next destination and get it there safely.

a. Frontier Detection Subroutine

The method of frontier detection for this initial map and all subsequently generated maps involves using the edge detecting techniques described above on the most current evidence grid map that the robot has at that time. Mapped obstacles or edges separate frontier regions. The centroid (roughly the center of a non-symmetric region) of each frontier region is marked as the robot's target destination for exploring that region.

Figure 12 illustrates the different parts of the frontier detection process. Figure 12(a) demonstrates an evidence grid built by a robot in a hallway next to two open doors. Figure 12(b) shows the frontier edge segments detected in the evidence grid by the frontier detection process. Figure 12(c) shows the frontier regions that are greater than some threshold value (in this case roughly the size of the robot). The centroid of each of the frontier regions is marked with a crosshair and numeric label. The frontier regions labeled 0 and 1 represent the open doorways and the frontier region labeled 2 is the unexplored portion of the hallway. [Ref. 22]

b. Exploration Subroutine

Once the frontier regions have been found on the most current evidence grid map, the robot must decide which frontier to explore next. The path planner in the exploration code uses a relatively simple depth-first search on the evidence grid. It starts

at the robot's current position and attempts to select the shortest obstacle-free path to the centroid of the frontier region chosen as its next destination. [Ref 23]

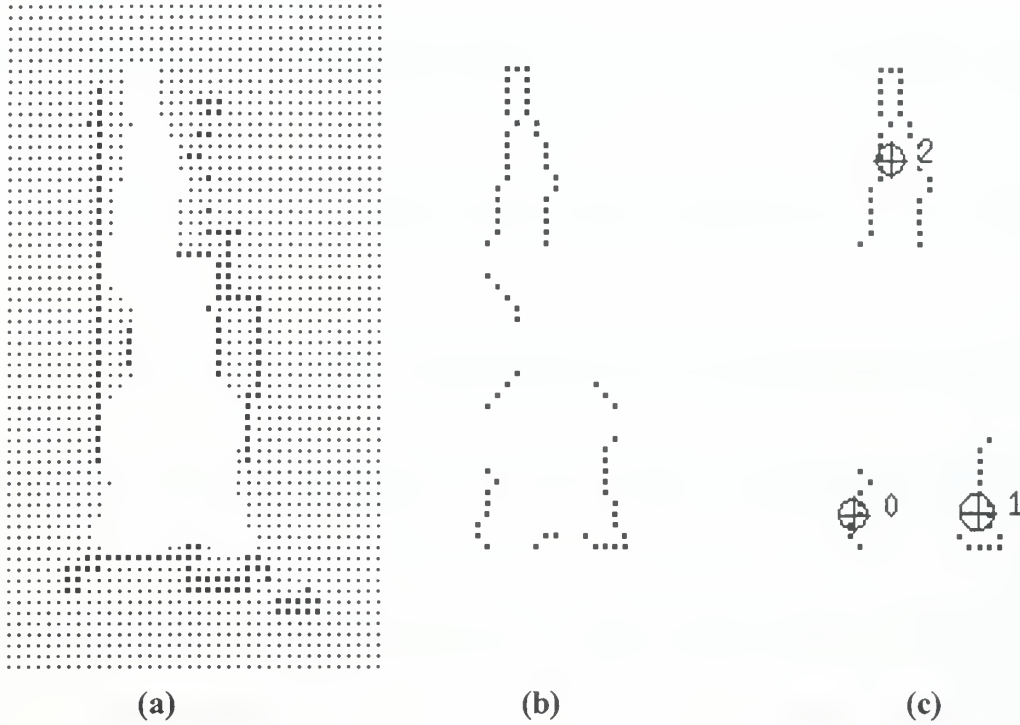


Figure 12. Example of frontier detection. From left to right: the evidence grid constructed, the frontier edge segments, and the frontier regions with the centroid of each region labeled. (From Ref. [22])

c. Navigation Subroutine

Once the exploration subroutine has chosen a frontier to explore it is the goal of the navigation subroutine to get the robot to its intended destination in a safe and efficient manner. Using the path chosen by the depth-first search and a variety of reactive obstacle avoidance behaviors the navigation subroutine guides the robot. The navigation method used in the exploration code is sufficient to allow the robot to steer

around small obstacles in order to get back on the pre-selected path. If the robot becomes blocked or for some other reason cannot make any progress toward its destination, then after a certain amount of time, that location will be added to the list of inaccessible frontiers that the robot cannot reach. At that point the robot will conduct another sensor scan, update its current evidence grid map, and attempt to navigate to the next accessible, unknown frontier as chosen by the exploration subroutine.

4. Integrating New Scan with Current Map

The map integration routine uses the method described in Chapter III for fusing the new sensor data onto the current map. The frontier-based exploration process uses a modified version of the log-odds Moravec code described in [Ref. 17]. In the NRL code, each cell of the evidence grid is assigned a value from -127 (definitely empty) to $+127$ (definitely full) for its occupancy value.

When the sensor fusion procedure described earlier is used to combine the current map data and the new scan data, the result will be a new map that reflects the effects of the most current sensor data. Similar data between the current map and the new scan will tend to reinforce one another driving well-mapped cells toward a floor value of -127 or a ceiling value of $+127$. Likewise, if the data in the new scan conflicts with the data in the current map, occupancy values of those cells will be driven toward smaller absolute values with zero representing a cell whose occupancy is completely unknown.

There is one important thing to note about coordinate systems used in the exploration process. When first initializing the robot, the user is asked to enter the

robot's X, Y coordinates and an initial orientation angle. For single robot exploration this is not necessarily required, as the robot could assume that its starting position and orientation are 0, 0 and 0 degrees and build a map around that point. However, for multiple robot exploration the robot knowing its starting position becomes very important as all maps sent to other robots are referenced to the shared global coordinate system. This will be discussed in more detail in the following chapter.

E. NPS IMPLEMENTATION ON SINGLE NOMAD SCOUT ROBOT

In order to use the frontier-based exploration code developed for the NOMAD 200 on the NOMAD SCOUT many modifications to the original NRL code are necessary. Throughout the original code there are many obvious, as well as hidden, dependencies and assumptions based around the sensor suite and mobility base of the NOMAD 200. Most of the modifications can be broken down into one of two categories: those changes due to the differences in the movement commands between the NOMAD 200 and the NOMAD SCOUT and those changes due to differences in the available sensors on the two platforms.

1. Mobility Modifications

As described in Chapter II, the NOMAD 200 has a three-wheel synchronous drive system with a turret that can rotate independently of the base, while the NOMAD SCOUT is a two-wheeled, two-degree of freedom differential drive robot which has no

turret. The NOMAD SCOUT was the first platform from Nomadic Technologies (manufacturer of all the NOMAD hardware and software products) that was built around such a mobility base. All their software prior to this had been designed for a three-wheel synchronous drive system with an independent turret. Early adopters of the NOMAD SCOUT, such as NPS, are using modified versions of the standard NDHE to interface with the new platform. Nomadic is currently developing a much more advanced version of the NDHE that will be more flexible in terms of working on multiple types of robots with varying mobility and sensor capabilities.

Fortunately, Nomadic has developed a set of macros that accept differential drive commands for the NOMAD SCOUT and transforms them into equivalent synchronous drive commands that the software understands. These modified movement commands convert the decoupled translation and steering commands used by the NOMAD 200 into differential drive values required for the NOMAD SCOUT. So when the software is controlling NOMAD SCOUT it is actually modified synchronous drive commands that are being sent to the robot. To eliminate any software conflicts due to the lack of a turret on the NOMAD SCOUT, the conversion macros send a null (zero) value in place of any turret rotation commands to the robot. [Ref. 10]

2. Exploration and Navigation Modifications

The exploration and navigation modifications from the NOMAD 200 to the NOMAD SCOUT are much more extensive than the mobility modifications. The assumptions about the sensor suite of the robot designed into the original frontier-based

exploration code make for a large number of modifications to work on the NPS research platform.

a. Elimination of Laser-Limited Sonar Dependency

In the original frontier-based exploration process the laser-limited sonar technique described above is used to scan whenever the NOMAD 200 reaches a new frontier. Since the laser rangefinding system is fixed in place on the NOMAD 200 turret, this involves rotating the turret a complete 360° while the base of the robot remains in place. There is also an option to use only the sonar sensors to scan at new frontiers. If the sonars are being used as the only sensor, there is another option to rotate the turret through the 22.5° arc that separates the sonar sensors and take sonar readings at intervals along that rotation.

In theory this gives the sonar sensors more opportunities to see obstacles from varying angles that might be less affected by specular reflection due to variations in the obstacle surface and what portion of the obstacle is struck by the sonar pulse. By modifying this sonar-only option to turn the entire robot instead of just the turret, it is possible to use this process on the NOMAD SCOUT in order to complete a sonar sweep upon reaching a new frontier. In addition, switching to the sonar-only option removes the dependency on a laser rangefinding system that the NOMAD SCOUT lacks.

b. Compensation for Inability to Timestamp Sonar and Pose Data

Originally it had been thought that once the laser-limited sonar dependency had been removed, that it might be possible to have the NOMAD SCOUT collect sonar

range data while on the move and eliminate the need to stop at frontier boundaries in order to collect new sensor readings. Taking sonar readings while moving can present a problem because sensor readings are not instantaneous and the robot's position or the environment can change significantly between acquisition and processing of the sensor data, thus causing the collected data to be inaccurate [Ref. 12].

At the speeds both the NOMAD 200 and NOMAD SCOUT typically travel this does not cause any difficulty for the reactive obstacle avoidance routine, but it can cause problems for the accuracy of the mapping routine. On the NOMAD 200 it is possible to attach the robot's pose information and a timestamp to every sensor reading so that data taken while the robot is moving can be correctly interpreted. The NOMAD SCOUT lacks this capability. In order to ensure that the sensor readings and pose information were as closely matched as possible it was necessary to break the sonar sweep at new frontiers (as described above) into small, individual movements. After each movement the robot was halted, the sonar readings were taken, and the sweep was continued. This has the effect of slowing down the overall mapping effort and the repeated small movements tended to increase the localization error.

c. Specular Reflection Minimization and Side Effects

In another one of the exploration code files (*grid.h*) it is possible to set the range at which sonar return data is considered "trustworthy." Because the NOMAD 200 has a laser rangefinder to confirm those sonar readings it is possible on the original code to leave this setting relatively high and disregard false readings. In the original code this

maximum sonar range is set at ten feet from the robot. Since the NOMAD 200 lacks a method of double-checking its sonar data this value is reduced to six feet. This also helps reduce errors due to specular reflection because it has been found that specular reflection errors are more prevalent at longer ranges [Ref. 28].

Unfortunately, there is an undesired side effect of reducing the “trustworthy” sonar range on the NOMAD SCOUT. With the decrease in range also comes a proportional decrease in the amount of new territory that is mapped whenever the robot reaches a new frontier. Mapping less area each time leads to an increase in the number of new frontiers to which the robot must travel in any given area to be explored compared to the number of frontiers with a longer sonar range. Increased travel leads to a faster buildup of localization errors when only dead reckoning from the robot’s odometric encoders is used to determine the robot’s position in the global coordinate system. Neither the original NOMAD 200 nor the current NOMAD SCOUT versions of the frontier-based exploration system incorporate any sort of localization error minimization process. Later work on the NOMAD 200 has included work with a continuous localization process [Ref. 20, 22] and it is hoped that this method or one like it may also be used on the NOMAD SCOUT in the future.

d. Reactive Obstacle Avoidance

While navigating to a new frontier, the reactive obstacle avoidance subroutine of the original exploration code uses the infrared sensors as well as the sonar sensors on the NOMAD 200 to detect nearby objects. The NOMAD SCOUT lacks

infrared sensors and it is necessary to remove any dependency on them and rely solely on the sonar sensors during the navigation and movement process.

It is also necessary to make some relatively minor modifications to routines that take into account the robot's size when determining if there is enough open space in a doorway or corridor for the robot to safely travel. The diameter of the NOMAD SCOUT is slightly less than that of the NOMAD 200 and thus it can move into a more constrained space.

V. MULTIPLE ROBOT INTEGRATION

Even a very capable and very well equipped single reconnaissance robot will still be restricted in the amount of area that it will be able to cover in a given time by the limits of its mobility base and the range of its sensors. In addition, a single robot reconnaissance system is very vulnerable in that a single failure on the one platform can have catastrophic consequences on the ability of the system to perform its mission. By combining multiple robots together into a single integrated reconnaissance system, it is possible to have a greater area of coverage in a given time, quicker coverage of a given area, and continuous or overlapping coverage of high value target areas of interest. In addition, the use of multiple robots provides for a graceful degradation, rather than failure, of the system if individual robots fail to perform for some reason. In Chapter IV the mechanics of a possible single-robot exploration system were discussed. In this chapter the dynamics of using multiple numbers of such robots will be explored.

A. CENTRALIZED VERSUS DISTRIBUTED CONTROL

There are two differing philosophies concerning command and control of multiple robot systems. The centralized approach advocates some sort of supervisor or controller process that receives inputs from the individual robots and provides information and commands back to them. The distributed approach calls for processing sensor data at the local level and individual robots making autonomous “decisions” based on that information. Between these two methods there is a wide range of combinations and

permutations depending on the intent of the system designers and how they choose to implement the system.

In the case of extremely centralized control there may be very little on-board “intelligence” on any of the individual robots and all commands of any sort (including motor and actuator commands) may have to come from the supervisor process. In this case the individual robots are little more than remote sensors on a mobility platform teleoperated by a central controller. The advantage of such a system is that each individual platform may be cheaper per unit. The main disadvantage is that highly centralized control leads to a single point of failure for the entire system and it will most likely also have a high bandwidth requirement if all raw sensor data and motor commands are required to be sent over the air [Ref. 29]. Another, less centralized, system may allow for centralized collection of processed sensor data from the individual robots which is then sent out to all the robots which then independently choose their own destinations for further exploration. Yet another system may call for the supervisor process to explicitly designate where individual robots will travel to and what tasks they will perform.

In a fully distributed system each individual robot might operate completely autonomously of the rest of the system. More autonomy on individual robots can lead to increased complexity and unit cost per platform, but it also allows elimination of the single point of failure problem that plagues highly centralized systems. Autonomous operation does not preclude cooperative effort between robots, but without a central supervisor it can complicate the problem of coordination. Lack of coordination in a

distributed system may lead to decreased efficiency and possibly even counterproductive behavior on the part of individual robots in respect to the goals of the system. This will be discussed in more detail in Chapter VI.

B. SENSOR FUSION

The evidence grid based mapping technique as described in Chapter III provides a good basis for the integration of sensor data from multiple, geographically separated robots. Sensor readings from different robots are fused in the same manner that sensor readings taken from a single robot at multiple locations are fused together. All that is required is that the sensor readings be referenced to a common global coordinate system in order for the sensor data from multiple locations to be properly correlated.

The details of how and where the sensor fusion is done will vary depending on the organization of the rest of the system. In a centralized system the coordinator/controller might receive all the individual robot sensor readings, fuse the data into a new global map, and redistribute that information throughout the system. A more robust distributed system might allow for each individual robot to receive all the other robots sensor readings (or at least those nearby), perform the sensor fusion locally, and “decide” for itself where to explore next based on some given criteria. Other implementations might allow for limited local processing of sensor data at the individual robot level with the resulting details transmitted to a remote higher level supervisory process.

C. COOPERATIVE EFFORT

In order to maximize the efficiency of a multiple robot system there has to be some degree of cooperative effort on the part of the individual robots. There are many possible degrees of cooperation as well as a multitude of methods and means of implementation. Both communication and coordination may be explicit or implicit with many varying combinations in-between.

1. Explicit Communication and Coordination

An explicit communication model allows for directed communications between each individual process and every other individual process as well as to and between any controlling or supervisory processes as well. While this model allows for a high degree of coordination and control, it can also become a communications nightmare very rapidly. The number of required links, L , for N separate processes in a fully interconnected system is given by:

$$L = \sum_{i=1}^{N-1} i \quad (1)$$

Another variation of this communication model is to use a few, or even just one, common broadcast channel(s) and then to attach some form of addressing to each message sent. Each individual robot or process then listens to the common channel(s) for messages addressed specifically to it, ignoring all others. This provides much the same functionality of the totally interconnected model with much less communications complexity.

Explicit coordination involves the passing of directions or orders, as compared to simply information, from a process outside the individual robot in order to influence or direct the robot's actions. It removes a degree of autonomy from the individual robots (which may no longer have a choice about their tasks and behaviors) and moves the decision-making ability to a higher level. Explicit coordination is usually associated with a hierarchical organization, but it can also be implemented on a peer to peer level where all the robots may be "equal," but at least on a temporary basis one robot may be able to direct the actions of another [Ref. 30].

Explicit communication and coordination is exemplified by the process of a parking lot attendant directing cars into and out of the parking lot. The attendant is explicitly communicating with each of the vehicle drivers through a series of hand and arm gestures (often accompanied by verbal expressions). The attendant is also providing explicit coordination amongst all the vehicles and has a direct line-of-sight communication channel with each driver.

2. Implicit Communication and Coordination

Implicit communication calls for processes not to pass information directly to another process, but to still convey information in some manner to interested parties. This may involve some sort of display or broadcast on the sender's part, or the process or robot may have some sort of noticeable behavior that an outside observer can interpret [Ref. 31].

In general implicit communication has lower direct communication requirements from robot-to-robot or robot-to-supervisory process. However, there is a corresponding increase in the requirement for an individual robot to be able to interpret other robots' behaviors or displays and extract useable information from them. This requirement may have a great effect on the unit cost per robot depending on the complexity of the information implicitly passed from robot-to-robot or robot-to-supervisory process.

Implicit coordination involves a single robot interpreting the actions and behaviors of other robots in the environment around it and taking individual action in accordance with the general goals of the system. This calls for a higher degree of autonomy on the part of the individual robot in order for it to know when to do the "right" thing at the "right" time. Implicit coordination is generally associated with a peer-to-peer organization where all robots are "equal," but it can also be implemented in a hierarchical structure with "lower" robots taking appropriate cues from the behavior of "supervisor" robots and vice-versa [Ref. 32].

Implicit communication and coordination is perhaps best exemplified by the process of an audience leaving a theater at the end of a movie or play. Generally, there is no overarching supervisor directing people into line and out of the theater and people do not explicitly announce their intentions to move into line to those around them. Instead, each person observes the actions of those around him/her and making a decision on when and where to move based on their actions and behaviors and following the general goal of leaving the theater.

D. NRL IMPLEMENTATION ON TWO NOMAD 200 ROBOTS

The interprocess communications routines used in the frontier-based exploration code were developed by Bill Adams (adams@aic.nrl.navy.mil) at NRL's NCARAI facility. The NPS modified versions of these routines are available from Xiaoping Yun (yun@ece.nps.navy.mil) of the NPS ECE Department as part of the NOMAD SCOUT modified frontier-based exploration code. Relevant routines and their use will be discussed below and portions of the code will be reproduced in the appendices.

1. System Overview

There are a couple of processes in the NRL code that bear directly on multiple robot, frontier-based exploration. The two key parts of their two-robot system that are relevant here are the communications process itself and the process of a robot integrating another robot's map with its own.

2. Communication Process

In the NRL code for two-robot, frontier-based exploration information about the world is shared, but each robot maintains its own map and makes its own decisions about where to navigate [Ref. 25]. There is no higher level supervisory process directing the individual robots or coordinating their actions. Normally this would be thought of as implicit communication and coordination. However, the system has to make use of an

explicit communication architecture to emulate the implicit communication process due to the limitations of the available networking protocols.

Even though conceptually the process that is modeled is a peer-to-peer relationship the limitations of using existing TCP/IP networking tools preclude the system actually implementing this model. Instead, the original code simulates a peer-to-peer relationship using a standard client-server model. In the two-robot code the first robot is always designated as the server while the second robot is always the client.

Also, even though the model of the original code implies implicit communication, messages concerning new map availability are actually passed explicitly from robot to robot. It is also important to understand that in both the NOMAD 200 and the NOMAD SCOUT implementations that there is no controlling process actually running on the robots themselves other than low level motor controls in the robot's firmware. The controlling process of the robot is running on a remote UNIX workstation and all "communications" between robots is actually communication amongst the remote controlling processes. Also each controlling process is a client to the *Nserver* process. Figure 13 provides an illustration of how this is all connected together for a two-robot system.

As shown in Figure 13, all three processes, the *Nserver* and the two mobile robot processes, are running on the same UNIX workstation. In reality these three can all be on the same or separate workstations or any combination in-between as long as there is a shared memory location to which each robot process can write the map it will share with the other robot processes.

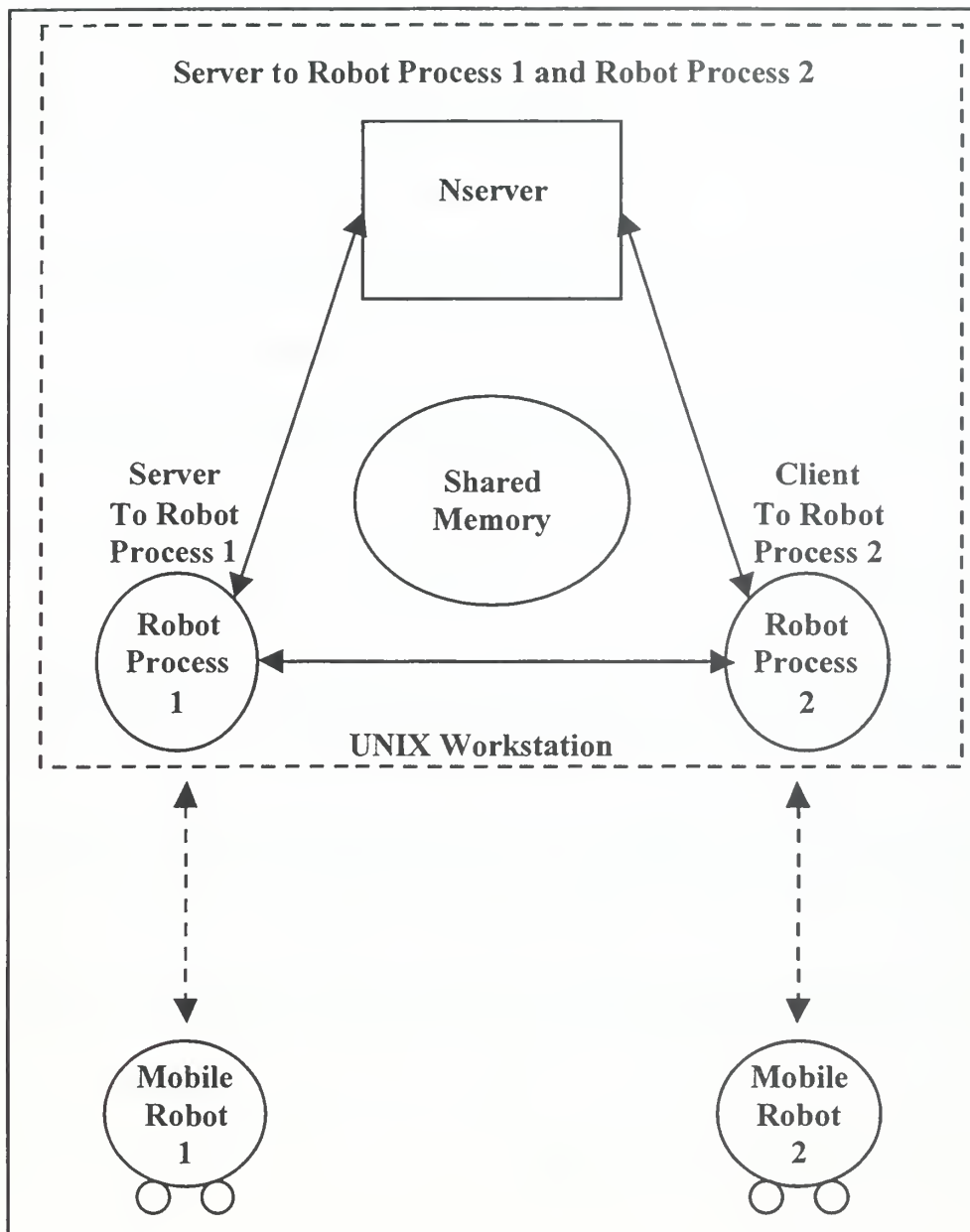


Figure 13. Illustration of the communication process used for the two-robot frontier-based exploration system.

During the exploration process whenever the individual robot completes a sensor sweep at a new frontier, its controlling process writes the result of that local scan into the shared memory location. This file (*local1.eg* or *local2.eg* depending on which robot process that creates it) is an evidence grid representation of the most current local map of

the area surrounding the robot of the controlling process. In the original representation this file is not the full global map maintained by each robot process.

After the robot process has finished writing the updated local map to the shared memory location it sends a message to the other robot process that there is a new local map available. This is a case where an explicit communication is used to simulate what would normally be a broadcast if allowed for by the network protocols being used. Instead of the updated map data itself being sent, there is a directed message to the other robot process transmitted.

After the update message has been sent to the other process the controlling process checks to see if it has received its own message from the other process indicating that a new local map file is available. If there is one available it reads it from the shared memory location and proceeds to integrate that new remote local map into its current global map. Using this method writing new maps, sending messages to other robot processes, and checking for remote local maps to integrate is only done after a new sensor sweep has been completed at a new frontier.

One of the drawbacks to this method is that it is possible for a robot process to miss a remote map update from another robot process. This can happen if a robot process is directing its associated robot on a long traversal from one frontier to a new one to be explored. It is possible for the other robot process to explore a frontier, write an updated map, move its robot to a new frontier, explore the new frontier, and overwrite the previous update all before the other robot reaches a new frontier and completes its exploration, writing, and remote map reading routines.

The original information is lost because the local map file that is written to the shared memory location only covers the immediate area around the robot. Once the robot moves to a new frontier and a new local map file is written it is very unlikely that there will be any map area overlap between the new map and the previous one. This can lead to a robot process making decisions on where next to explore based on incomplete information as to where other robots have already explored.

3. Integration of Foreign Maps

The integration of a foreign or remote local map uses the same methods described previously in Chapters III and IV for fusing new sensor data onto the current map. The sensor data from a remote map is fused with the robot process's global map in the same manner as if the process's associated robot had collected the same data itself. The important thing to note is that the remote local map must also have attached to it the global X and Y coordinates where the data was collected so that it may be registered correctly during sensor fusion with the global map.

E. NPS IMPLEMENTATION ON FOUR NOMAD SCOUT ROBOTS

In order to use the communications routines developed for the two-robot NOMAD 200 frontier-based exploration code on a greater number of NOMAD SCOUT robots a few modifications to the original NRL are necessary. None of the changes are actually specific to the NOMAD SCOUT so the modifications made here will work just

as well on an increased population of NOMAD 200 robots. It is hoped that other researchers with larger numbers of NOMAD 200 robots will be able to make use of the modified code developed at NPS. The modifications can be broken down into two parts: extending the client-server architecture to manage more than two robot processes and transmitting the global map vice the local map from the server robot process.

1. Extended Client – Server Model

There are a variety of possible different approaches to extending the original code's client-server model for two robots to a client-server model for greater than two robots. In order to maintain the fully interconnected architecture of the original NRL code it would be necessary for individual robot processes to function as both clients and servers depending on the circumstances. An example of how this might work for four robot processes is shown in Figure 14. A process being both server and client simultaneously is not without precedent as all the robot processes are also clients to the *Nserver* and the first robot process is also a server to the second robot process in the original model.

However, as seen in Figure 14, the number of interconnections increases rapidly as the robot process population grows. It becomes apparent that this is an unnecessarily complicated and unwieldy implementation for a large number of robot processes and an alternative method is used that while not fully interconnected between robot processes, still provides suitable connectivity for the transmission of remote map file information.

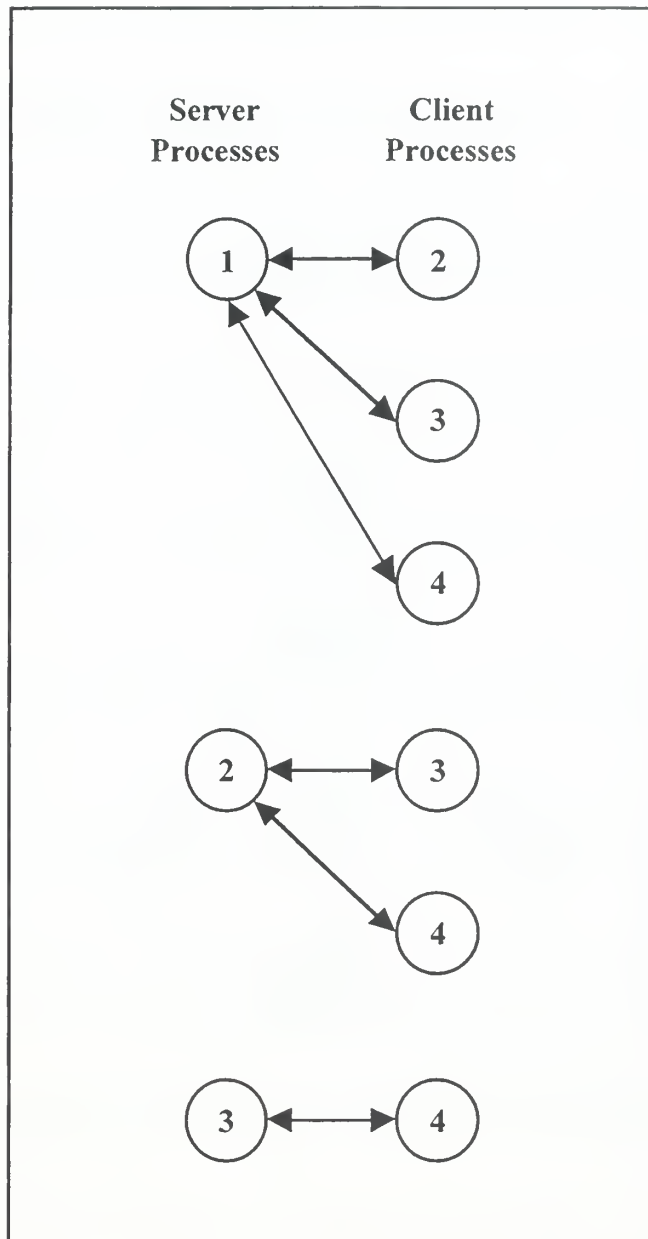


Figure 14. Illustration of a fully interconnected communications architecture for four robot processes using a client-server model.

Instead a single robot process is used as a server and all the other robot processes are clients to that single server process. This model is shown in Figure 15. As in the original NRL code the first robot process acts as the server. Also, it should be noted that all the robot processes remain clients of the *Nserver* program. This approach eliminates

the full interconnection of the original NRL model, but greatly simplifies the modification of the code to work for larger numbers of robots. However, without the direct connection from client process to client process there is a need for another way to transfer remote local map information between client robot processes. The solution to this problem is discussed in the next section.

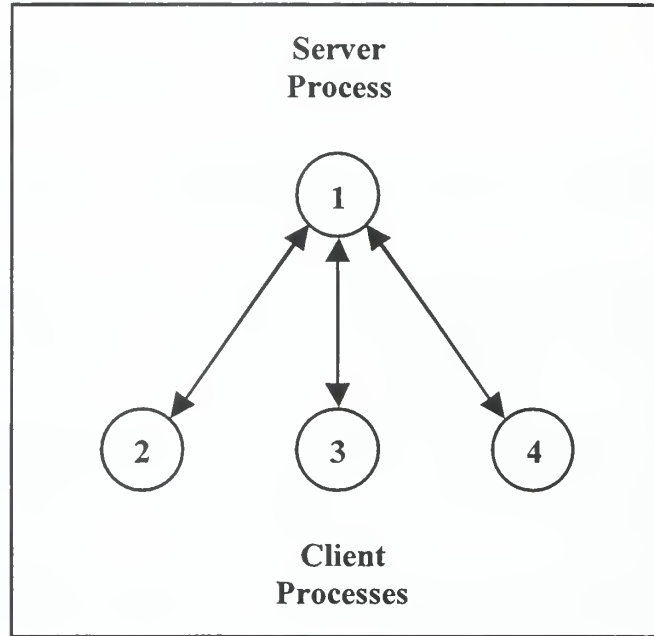


Figure 15. Illustration of the communications architecture implemented for four robot processes using a client-server model and retaining the single robot process as server.

In this model each of the client processes is in effect part of a two-robot system, itself and the server process. Only the server process “sees” all the individual client robot processes. However, there is still a good deal of robustness to the system. If one of the client process robots fails the rest of the system will continue to function in the same manner with the smaller robot population. If the server process fails there will be no more sharing of map data, but each robot process will continue to explore individually until there are no more frontiers remaining.

2. Transmission of Global vice Local Maps from Server

In the original NRL code whenever a robot process writes a map file to the shared memory location it is a local map file of just the immediate area surround the associated robot of that process and showing sensor data from the latest sensor sweep only. It is possible to modify the code so that instead of just writing the local map data, that the global map maintained by that process is written to the map file. This global map file incorporates all the separate local sensor sweeps that that process has made up to that time as well as any remote map files that it has fused into its global map.

Modifying the code in this manner makes it possible for each robot to write the entire evidence grid representation of its global map to the shared memory location (*globalx.eg* where x is the number of the robot process). In this manner the server process incorporates the individual global maps of all the individual client processes into its own global map. When the client processes read the *global1.eg* remote map file written by the server process they then indirectly incorporate all the results of the mapping done by the other client processes.

This also solves the problem of individual sensor sweeps being “lost” due to a short move, explore, write cycle causing the file to be overwritten. In the case of writing the entire global map the new global map will incorporate the previous sensor sweeps as well. However, having all the separate robots write their individual global map files has an unexpected drawback as well.

When only the local sensor sweep information is propagated from robot process to robot process then “bad” mapping data from one robot (due to sensor errors, location errors, etc.) may be overwritten when another robot happens to scan the same area. Also in this manner temporary obstacles (people, other robots, etc.) are steadily eliminated or their positions updated on the global map that each robot process maintains. By having each robot send its entire global map an unwanted feedback loop for the reinforcement of “bad” data can occur.

If a client robot scans an area that happened to have a temporary obstacle or is very “noisy” due to specular reflection off of objects in that area, the results of that local scan will be incorporated into its own individual global map. Now when that global map is read by the server process it will fuse that data with its global map and write its updated global map to the shared memory location for all the client processes to read. After they read it and update their global maps, the next time they write their global maps for the server process they will also show the same “noisy” or temporary obstacle sensor data which will reinforce the previous data on the server process global map. The server process will in turn write this updated global map for the client processes to read and the feedback of incorrect or out-of-date sensor data will continue. This is not a desired situation.

In the final version of the NPS modified code only the server process writes its global map for the client processes to read. The client processes write out only the results of their local sensor sweeps for the server process to read. In this implementation temporary obstacle data or “noisy” sensor data will be propagated through the system

once when the server robot incorporates it into its global map, but it will not be reinforced by having that same sensor data sent back to it from the client processes. The tradeoff to this approach is that once again the server process may miss a client process local map if the server process is busy controlling its robot during a long movement between frontiers.

VI. RESULTS

Despite equipment delivery delays and the need for extensive software development, substantial initial testing of the NOMAD SCOUT multiple robot frontier-based exploration system at NPS was possible in the limited time available for research. Besides the results presented here, the major product of this research was a demonstrable robotic exploration system that will serve as a testbed for future projects involving both single and multiple robots. Presented here are the preliminary findings to date.

A. SINGLE ROBOT MAPPING EFFORT

Single robot mapping of a given area provided a baseline against which multiple robot mapping efforts were compared as well as ensured that the basic frontier-based exploration code and evidence grid map making routine functioned properly in conjunction with the NOMAD SCOUT robot. Early tests were also used to determine the best combination of map grid resolution, “trustworthy” sonar range, and given area to be explored that would yield optimal results for a single robot. The best combinations of these variables were then used for each individual robot in multiple robot mapping experiments.

1. Single Robot Test Conditions

The test area for all single and multiple robot trials was an approximately 37 by 37 foot research room with two large test benches that defined three major corridors in the

space. An additional test bench along one wall further constricted one of the corridors. Figure 16 is a simple illustration of the area with annotations for the various starting positions used in the trials. The center of the room was defined to be the origin of the coordinate system used in the map produced during the robot mapping trials. This origin is marked as position zero in the illustration below. The various corridors are referred to as top, middle, and bottom as labeled in the sketch of the room. Note the windows stretching along one wall, the metal cabinets, and the large number of doors. These were geographical features that proved especially challenging during efforts to map the area due to specular reflection effects.

Shown in Figures 17, 18, and 19 are a series of pictures taken of the test area in order to provide the reader with a better perspective of the environment. Note the large open spaces under the test benches. Because the lower portions of these benches were so close to the ground the sonar sensors often failed to detect them. It was necessary to fill in some of the space under the benches in order to enhance their sonar image before any worthwhile results were possible.

Figure 17 shows the top corridor of the test environment. The metal desks and windows in this area proved particularly difficult to accurately map. Figure 18 shows the middle corridor of the test environment. This corridor runs down the center of the test environment and the midpoint of this corridor served as the origin of the coordinate system used in all the mapping trials. Again, the windows at the end of this corridor caused difficulties in the mapping trials. Figure 19 shows the bottom corridor of the test

environment. The smooth-surfaced doors and the metal cabinet in this corridor were the major sources of mapping errors.

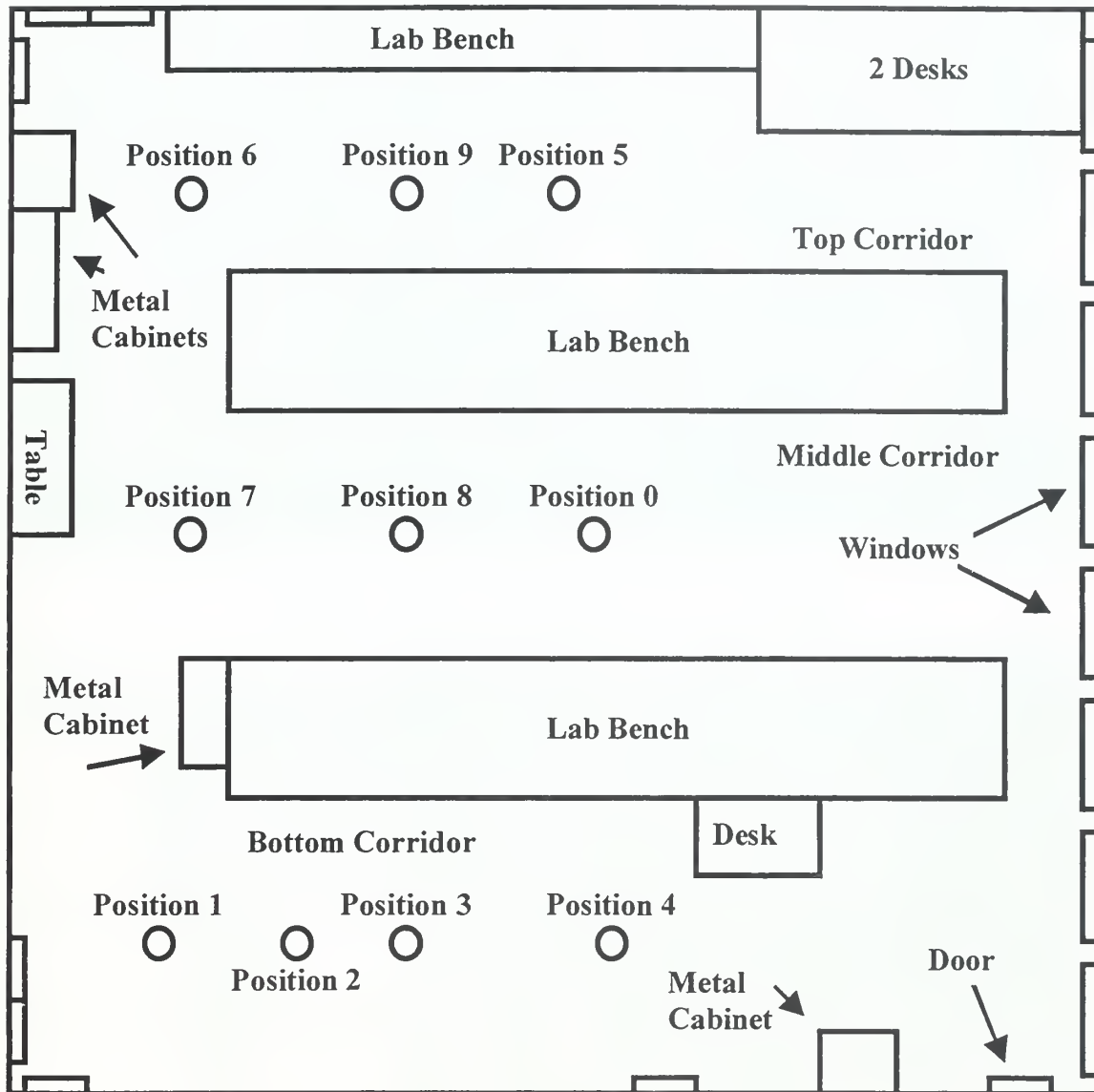


Figure 16. Simple illustration of test environment for single and multiple robot trials showing starting positions and significant geographical features.

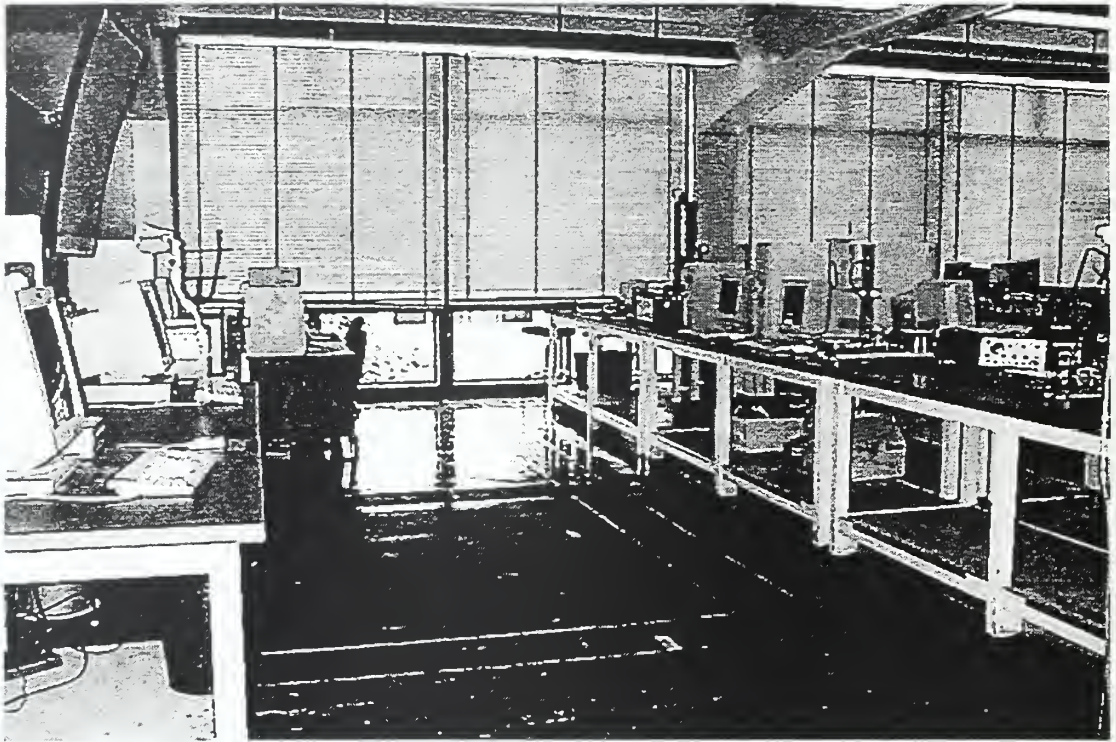


Figure 17. Top corridor of test environment.

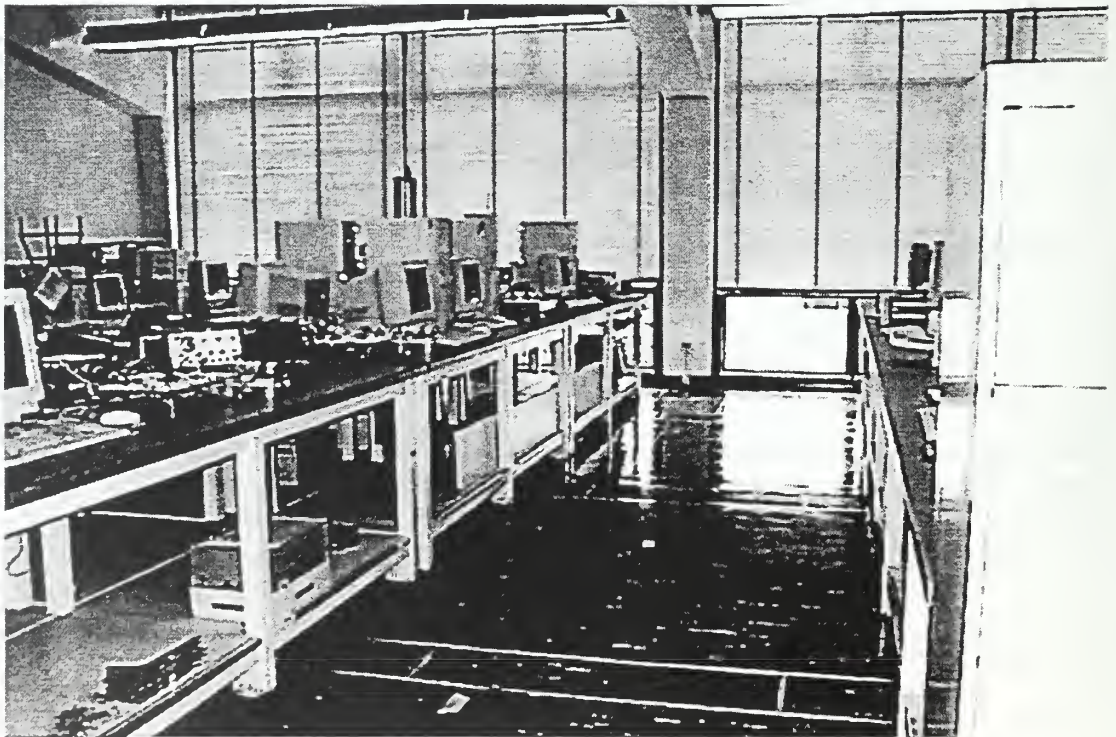


Figure 18. Middle corridor of test environment.

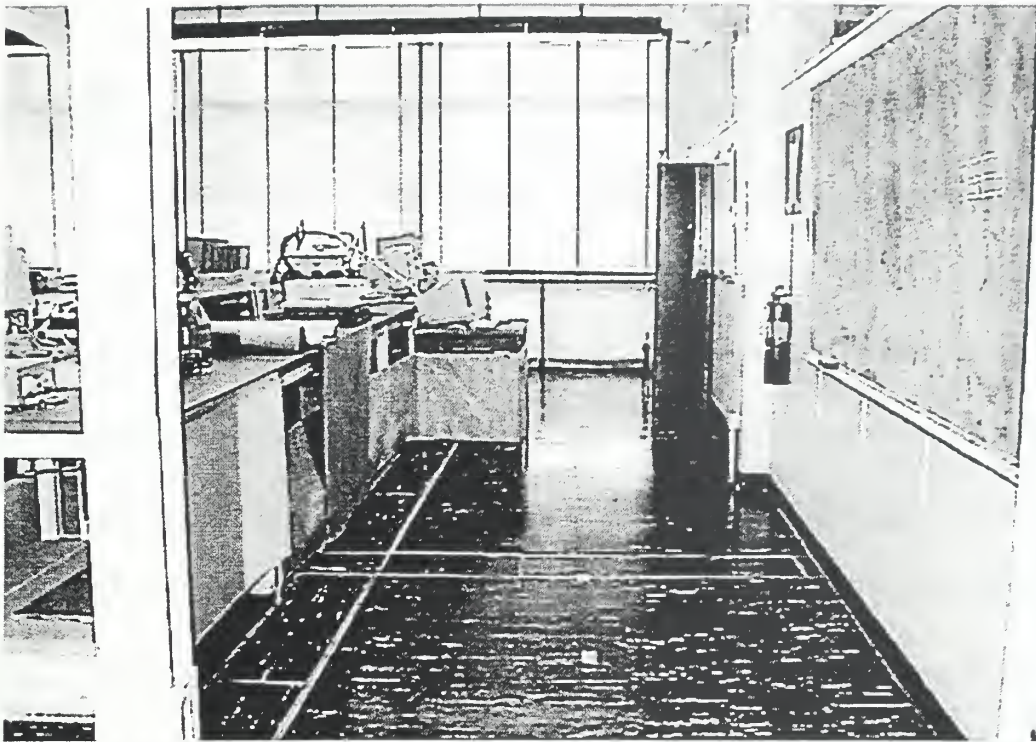


Figure 19. Bottom corridor of test environment.

2. Experimental Variables

After the basic robotic exploration and mapping system was functional it was decided to concentrate on examining a few easily-manipulated variables in order to attempt to optimize the system for the given test area.

a. Given Area to be Mapped

The first thought was to minimize the area the robot would be expected to map. This variable is set in the file *grid.h* and sets the size of the room the robot will map. Minimizing this would seem to ensure the finest detail possible for the given evidence grid resolution (as described below). It proved not to be practical to set it exactly to the actual size of the test area. In a perfect world the robot could have been

instructed to map a 37 by 37 foot room and all would be well. However, as odometry errors began to accumulate during a test run, the robot became confused near the edges of the room when its now-inaccurate odometric encoders indicated that it was outside the boundaries of the expected area.

In addition, specular reflection errors off of objects near the boundaries (especially the windows) caused false sonar returns from outside the boundaries set for the room. This caused additional errors. To alleviate these difficulties a 3.5 foot safety margin was added on each side of the room boundaries, resulting in a 44 by 44 foot area that the robot expected to map. This reduced the overall resolution slightly, but resulted in more consistently successful mapping efforts.

b. Evidence Grid Resolution

Also in the file *grid.h* the evidence grid resolution is set. In order for the evidence grid method to correctly fuse two different grids the grids must be symmetrical and a power of two. Varying resolutions from 64 by 64 cells to 512 by 512 cells were tested.

The initial testing with a setting of 512 by 512 cells resulted in very noisy sonar data and many small frontiers. These small frontiers were often found to be grouped around one large object, especially one with many projections such as a chair or table. It was hoped that setting a coarser resolution would result in quicker mapping of large areas and less noise from the arms or legs of chairs and tables. It soon became

evident that using a very coarse resolution, such as 64 by 64 cells, did result in a shorter mapping trial, but not for the desired reasons.

With the room size mentioned above of 44 by 44 feet and using 64 by 64 cells in the evidence grid, each cell was about 68 in^2 or 8.25 inches on a side. This is a rather large size for a cell compared to the size of objects in the test environment. As expected, the noisy sonar returns were blurred into fewer cells, but the unfortunate side effect was that now large cells that were only partially filled were marked as completely filled, whereas with finer detail these areas would have been resolved into open space. With the coarse detail setting the robot soon marked all possible paths as blocked by obstacles when in fact there was still many open paths for it to travel. This is illustrated in Figure 20. Here the resolution was set at 64 by 64 cells and the robot was started at position zero in the center of the room. Even though the corridor was open, noisy returns were still blurred together to the point where the robot determined that it was completely blocked.

Numerous trial-and-error investigations led to the choice of 256 by 256 cells for the grid resolution in conjunction with the “trustworthy” sonar range discussed below. Again using the room size of 44 by 44 feet, but now with 65536 cells, each cell in the evidence grid was approximately 4.25 in^2 or less than 2.1 inches on a side. This was the best compromise found between reducing noisy data and having fine enough detail to navigate the robot and map properly. It is important to note that these results were specific to the environment the mapping tests were conducted in and will most likely be quite different in dissimilar circumstances.

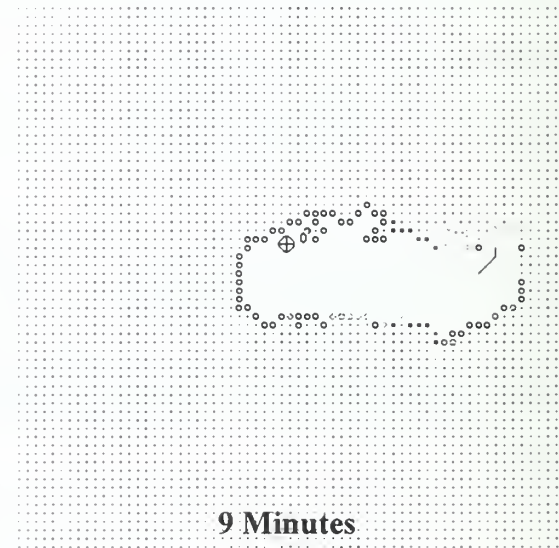
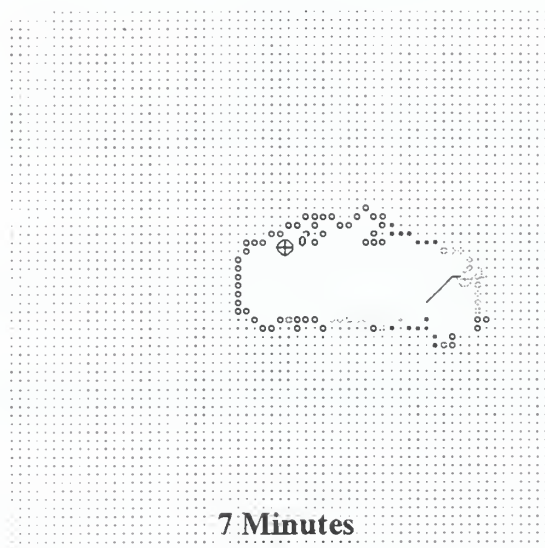
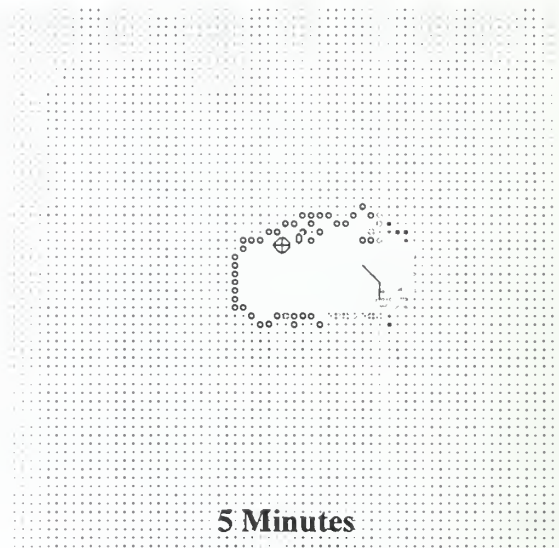
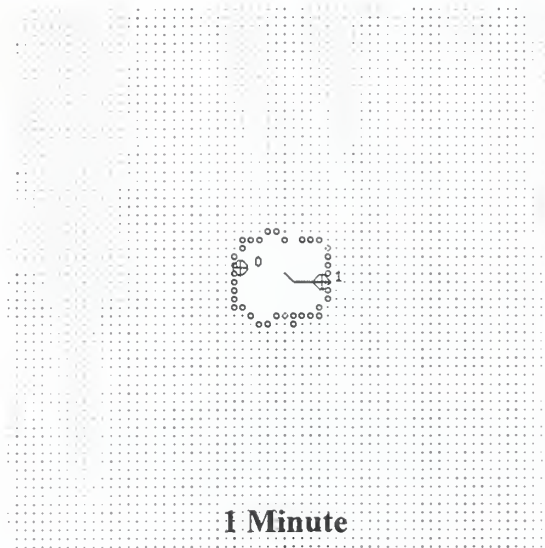


Figure 20. Illustration of robot exploring corridor using coarse discrimination (64 by 64 cells). Large individual cell size causes false determination that ends of corridor are blocked.

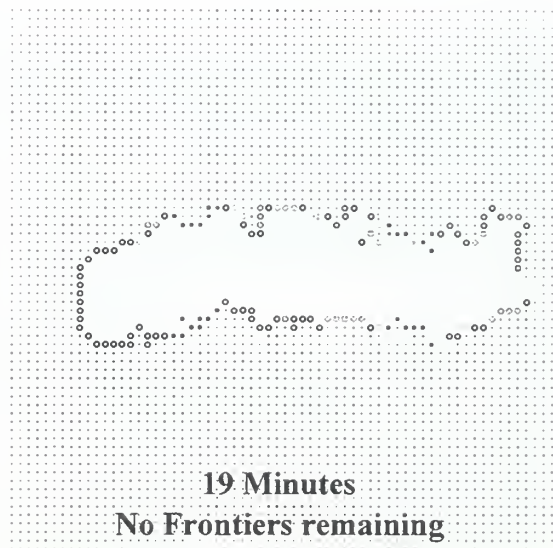
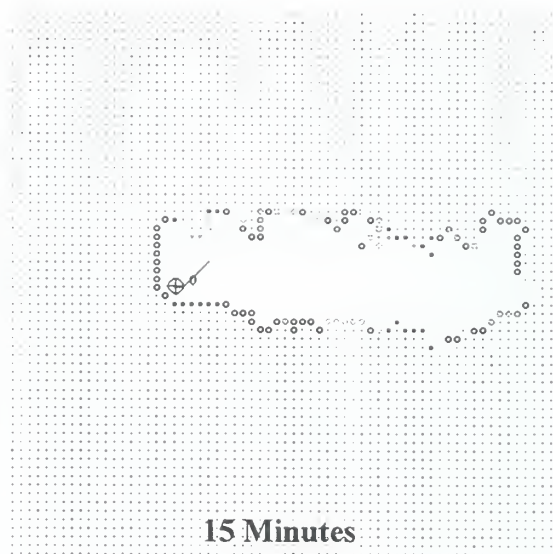
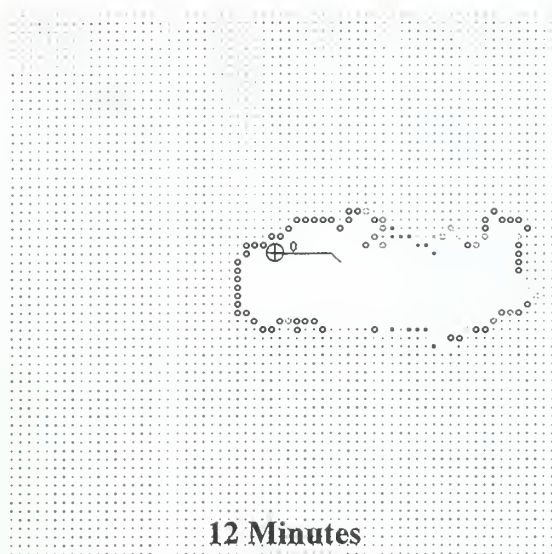


Figure 20 continued. Illustration of robot exploring corridor using coarse discrimination (64 by 64 cells). Large individual cell size causes false determination that ends of corridor are blocked.

c. *“Trustworthy” Sonar Range*

The final option that was manipulated in the *grid.h* file was the *MAX_SONAR_RANGE* variable. This variable sets the “trusted” range for sonar sensor readings. Readings indicating distances further away than this setting will be disregarded for the purposes of map building and exploration. As was mentioned earlier, setting this to a lower value than the 10 foot range used with the NOMAD 200 seemed to be the best way to reduce the problem of specular reflection. Also, as mentioned previously, there was a penalty in setting this too low in the increased amount of travel the robot would be required to do and the subsequent increase in localization error.

After many trials it was found that a six foot range was adequate to reduce many (but not all) specular reflection effects and did not seem to compromise the robot’s localization capability to any great degree. However, if an additional localization method is added to the NOMAD SCOUT platform in the future it is recommended that this range be further reduced in order to further mitigate specular reflection problems. Figure 21 shows a sequence of maps created during a NOMAD SCOUT mapping sequence with the *MAX_SONAR_RANGE* set to 10 feet and a grid resolution of 256 by 256 cells. The robot was started at position zero in the center of the test area. Note the numerous and extensive specular reflection effects from the areas near the benches and windows. These false returns created numerous small, false frontiers that the robot attempted to explore, but could not reach.

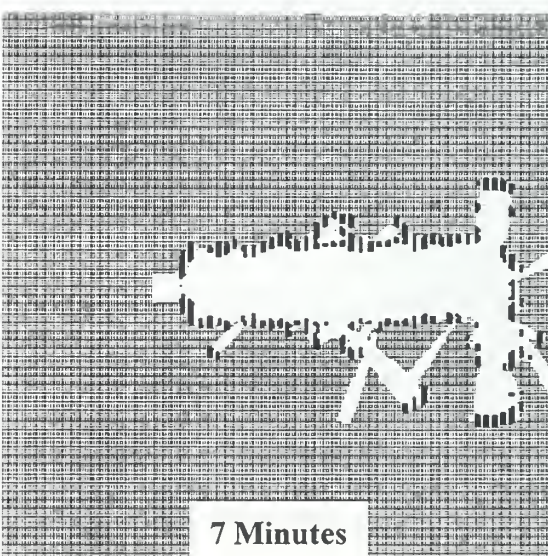
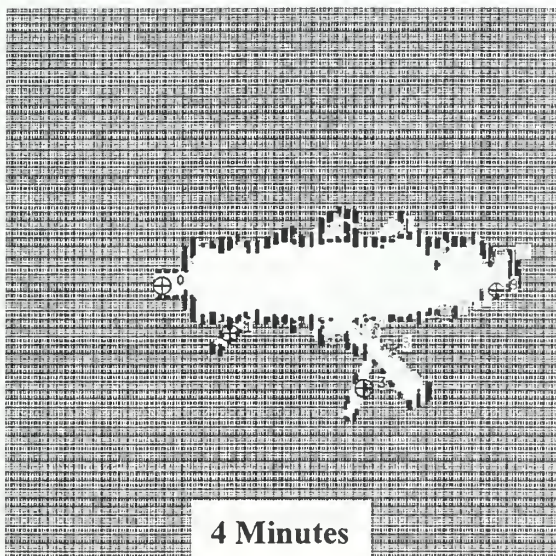
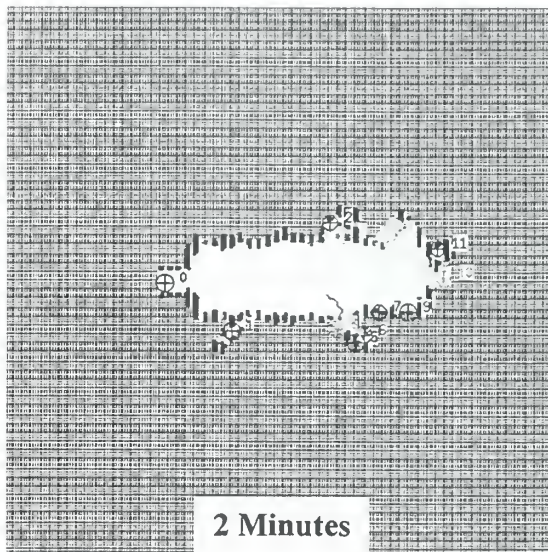
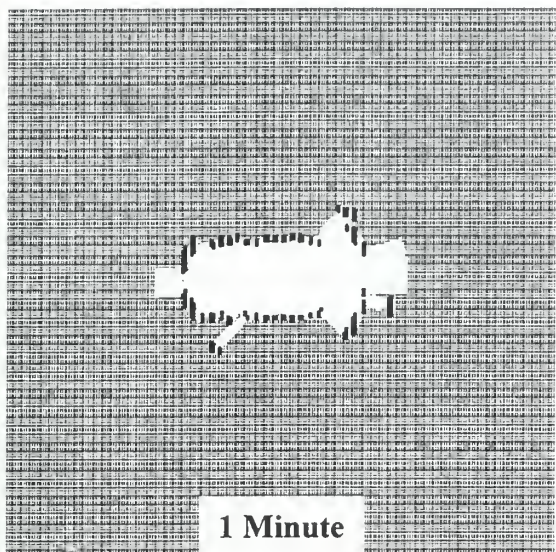


Figure 21. Illustration of false sonar returns and subsequent poor mapping results due to extensive specular reflection when using 10 foot sonar range.

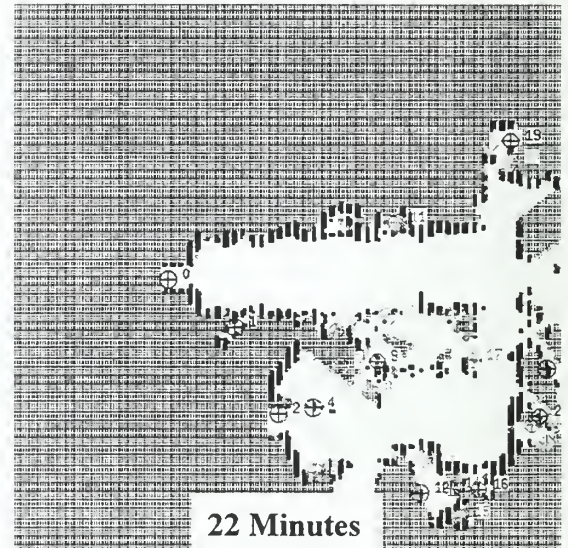
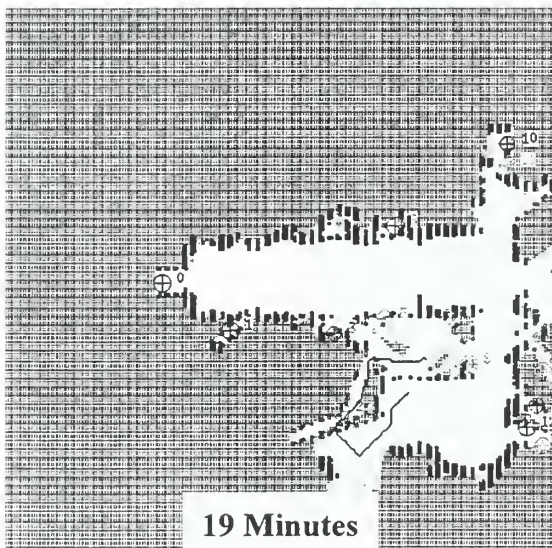
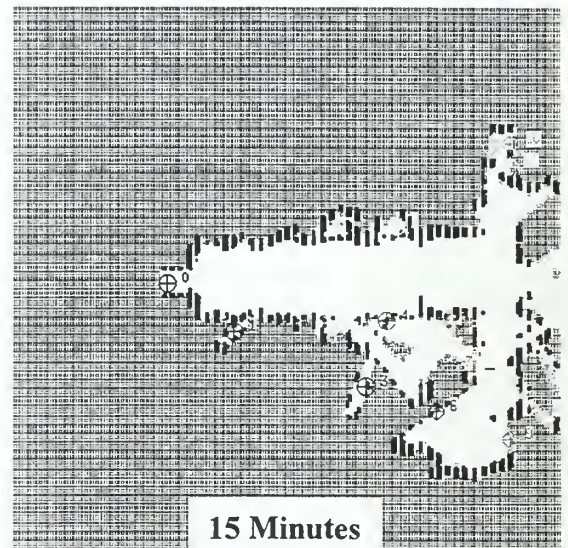
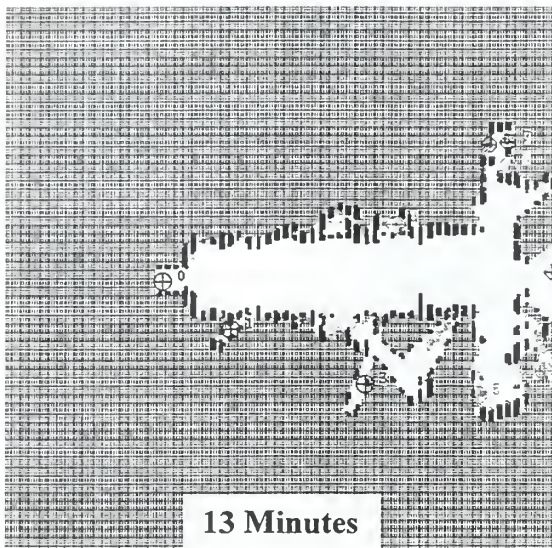


Figure 21 continued. Illustration of false sonar returns and subsequent poor mapping results due to extensive specular reflection when using 10 foot sonar range.

3. Trial Runs and Results

One thing is immediately noticeable from the many trial runs conducted with one robot in the initial research: as currently implemented no single robot alone will be able to map the entire test area. On average, after 20-25 minutes of travel the odometry errors

become so large that further mapping efforts are actually counterproductive. Continued mapping at that point, with localization so badly compromised, will most likely begin to overwrite previously accurate areas of the evidence grid map with inaccurate data. This was seen many times in longer trials. In the current implementation there is not enough time before odometry error becomes fatal to the exploration and mapping effort for the robot to cover the entire space. Thus the need for multiple robot exploration and mapping is evident.

Figure 22 illustrates a typical trial run with the “standard” settings of a 256 by 256 cell evidence grid resolution and a maximum trusted sonar range of six feet. This run was started from position zero in the center of the test area. Mapping efforts continued well for about the first 15 minutes. After that time, localization errors began to interfere with the robot’s ability to navigate to new frontiers. Localization continued to get steadily worse, especially rotational tracking. By the 21st minute of the experiment the robot was actually travelling in the opposite direction than it indicated that it was moving. This seemed to be a common trend among many of the trials. The small movements that the robot makes during sonar sensor sweeps at new frontiers as well as the many small turning motions the robot makes as it travels seem to affect the rotational localization much more quickly and much more detrimentally than the translational localization.

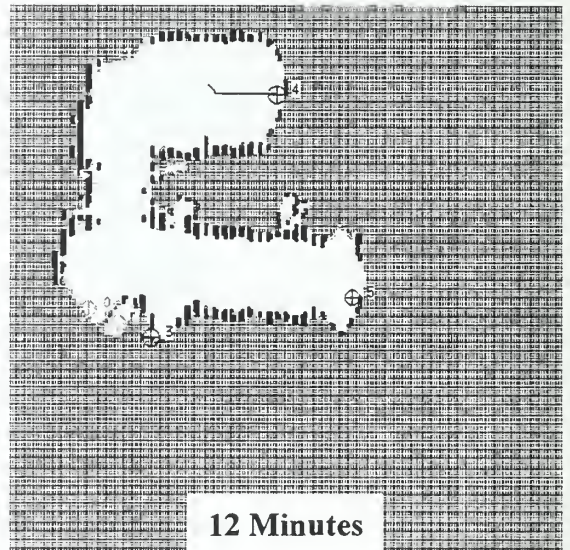
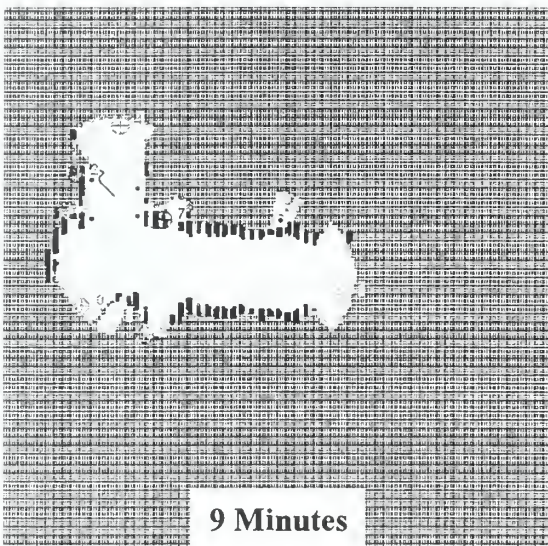
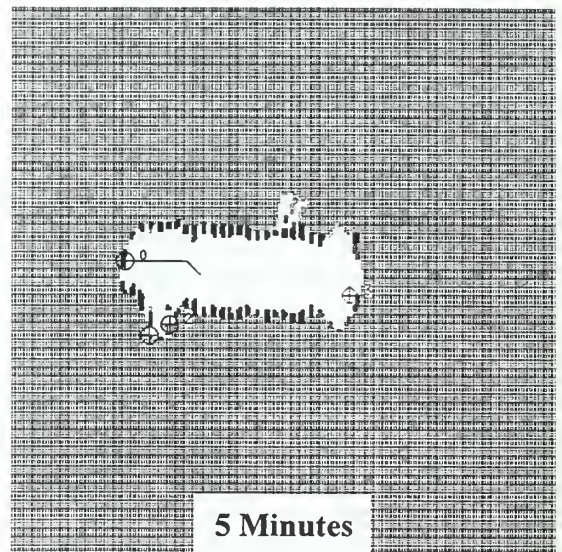
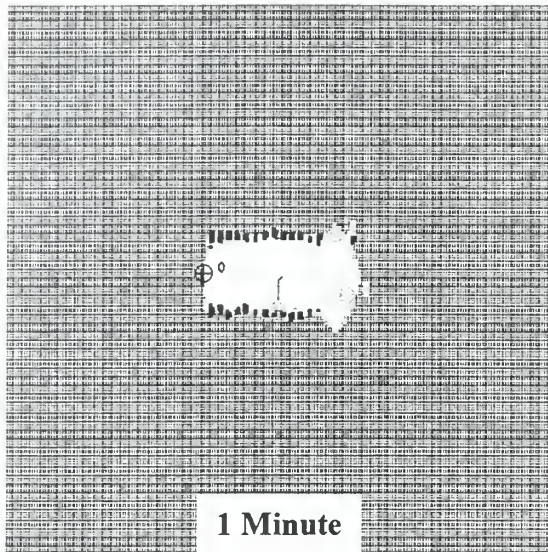


Figure 22. Illustration of fatal localization error beginning about 15 minutes into the mapping and exploration phase.

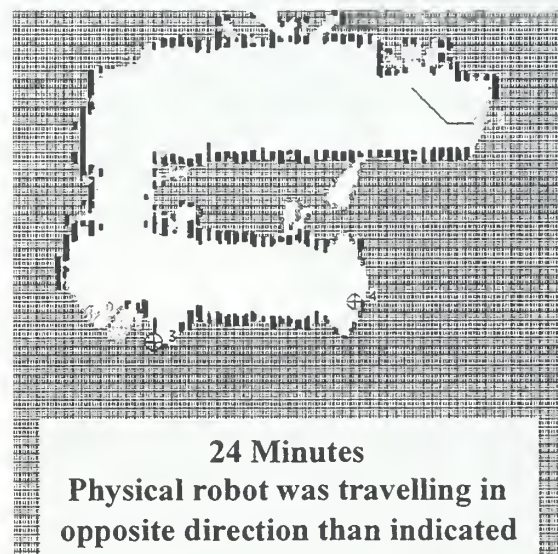
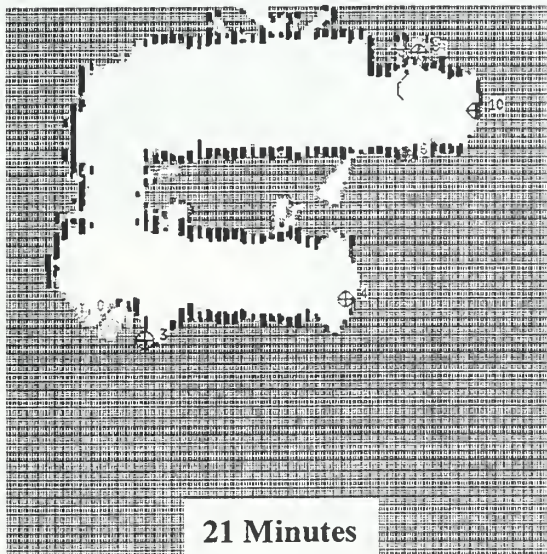
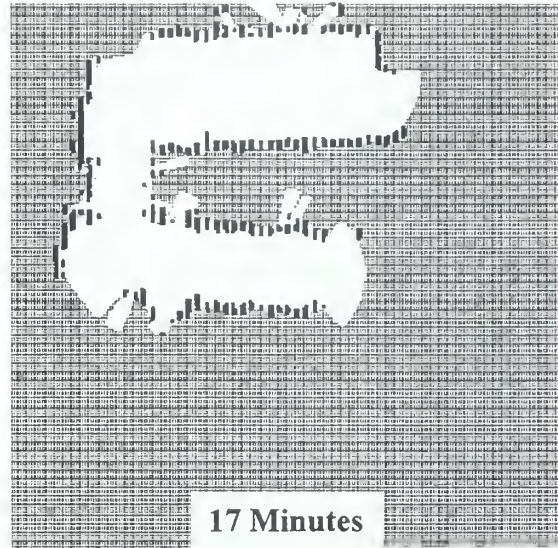
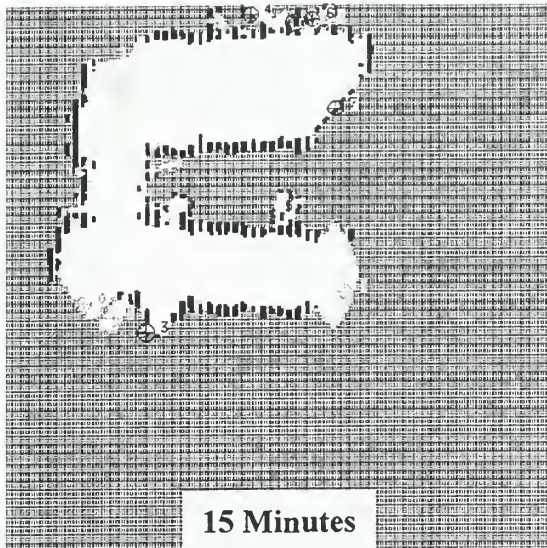


Figure 22 continued. Illustration of fatal localization error beginning about 15 minutes into the mapping and exploration phase.

However, other trials showed that localization errors could also cancel each other out and allow longer periods of mapping. These maps will be distorted compared to the actual “ground truth” of the area mapped, but they will still have recognizable, albeit distorted, geographical features such as corridors, corners, etc. Figure 23 is an example of such a trial. This run was conducted under the standard conditions with the robot

initially started at position one. Between the nine and 19 minute point in the trial the robot was stuck in a small area between the two benches trying to explore many small, inaccessible frontiers. By the time it “broke free” its odometry was obviously distorted, but it was possible to still recognize map features produced for another 12-14 minutes.

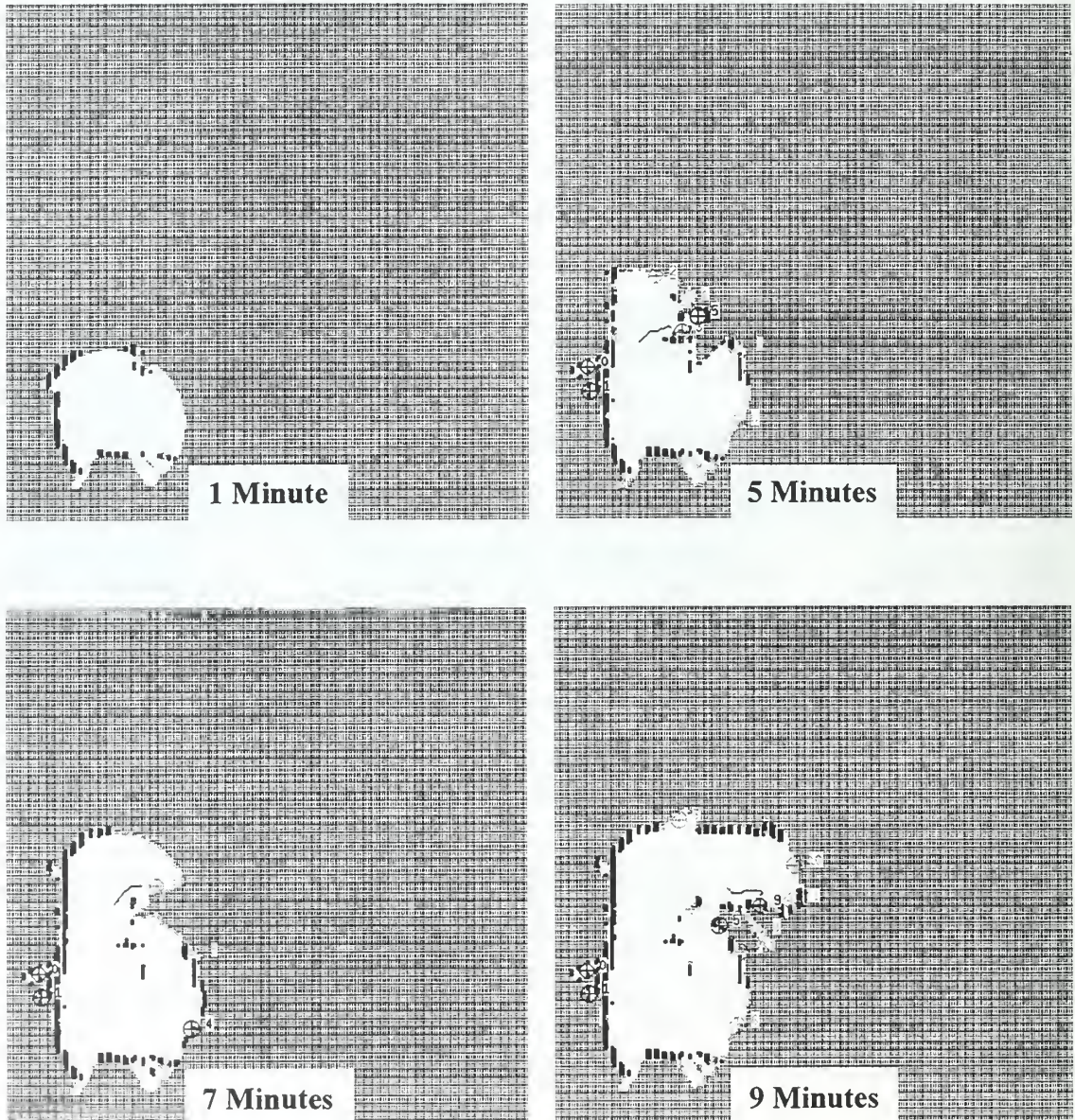


Figure 23. Illustration of robot getting temporarily trapped in a small area, breaking free, and then continuing to produce a recognizable, although distorted, map for several minutes longer.

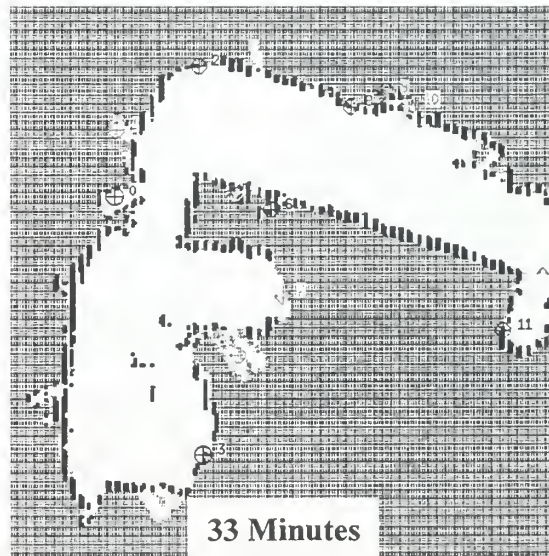
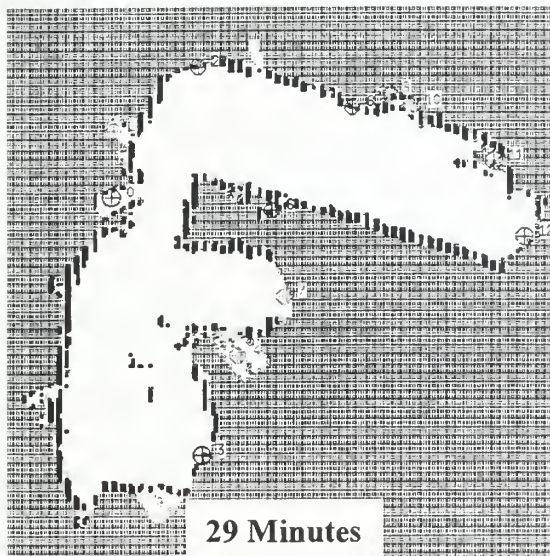
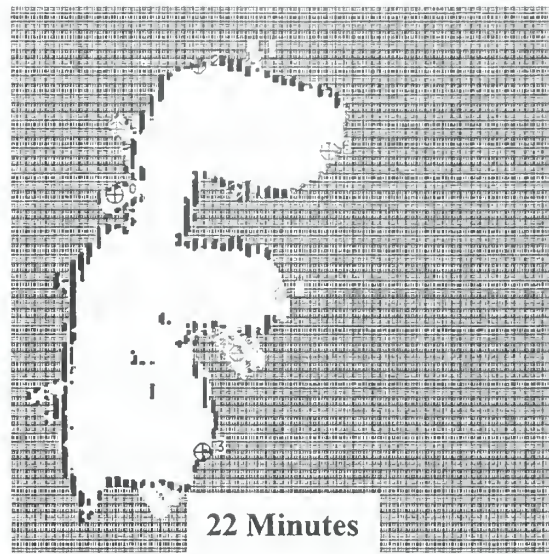
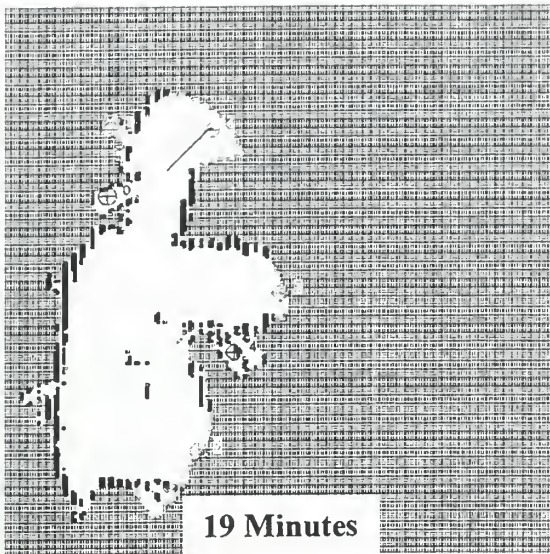


Figure 23 continued. Illustration of robot getting temporarily trapped in a small area, breaking free, and then continuing to produce a recognizable, although distorted, map for several minutes longer.

All single robot trials continued to point toward the need for multiple robots acting simultaneously in order to map the test area. Under the current implementation a single robot cannot map the area before localization errors render it incapable of further exploration and mapping.

B. MULTIPLE ROBOT MAPPING EFFORT

Multiple robot mapping efforts provide a number of mixed results. In some circumstances the use of multiple robots dramatically decreases the amount of time required to map a given area compared to a single robot mapping the same area. In fact in some cases multiple robots were able to map an area that the single robot could not complete due to buildup in localization errors. However, under other circumstances multiple robot mapping can be less efficient than expected and actually worse than single robot efforts. There also appear to be some issues with the effects of controlling many robots simultaneously on network performance and reliability.

1. Multiple Robot Test Conditions

The test area for all multiple robot trials was the same as for the single robot trials, the 37 by 37 foot research room described previously. All robot processes, as well as the *Nserver* program, were run on the same Sparc 20 workstation used for the single robot trial and the robot processes controlled their respective robots via the same wireless Ethernet connection. Using the same workstation to run all the robot processes simplified the sharing of map data between the client and server processes, but did lead to an overall slowdown in the speed at which the individual processes ran as more robot processes were added. For all the multiple robot trials each individual robot was similarly configured with an evidence grid resolution of 256 by 256 cells and a trusted sonar range of six feet.

2. Trial Runs and Results

One major finding from the multiple robot trials was that there was not quite the consistency or quality of performance improvement that had been expected. In a perfect implementation if a single robot can map X area in Y time, then N robots should be able to map X area in Y/N time (or conversely map $N*X$ area in Y time). While such extreme levels of performance improvement were not expected at this point in the research, it was expected that there would be somewhat more improvement and more consistency in improvement than was seen. This will be discussed further below.

3. Beneficial Effects

Some multiple robot trial runs did show significant improvement in mapping efforts over single robot trials. This was especially true when the robots started in widely varying geographical positions in the test environment with well-known initial starting coordinates. In these cases each robot mapped its local area in the same manner as in the single robot trials and the server robot process consolidated the map data. Figure 24 illustrates this process for an average two-robot trial.

In the trial shown in Figure 24 one robot was started at position zero and the other robot was started at position five. With the two robots separated by an obstacle (in this case one of the benches) they explored their general area without interference from each other. One important thing to note about this trial is that the robot in the middle corridor suffered networking problems after approximately 20 minutes. It stopped

mapping, but the robot in the top corridor continued mapping. This illustrates the benefits of a distributed system without reliance on a central controller to operate.

As the still functioning robot continued to map the top corridor localization errors soon began to degrade its navigation capabilities after about 23 minutes. At the 30 minute point in the trial further mapping efforts are futile. Note the specular reflection effects on the robot in the middle corridor near the windows and along the benches in the middle corridor.

Figure 25 illustrates a representative three-robot trial with the robots starting in widely separated positions. In this case the robot were started at positions two, eight, and nine. Again, each robot began to explore its local area without interference and the server robot process collected the local sensor data from each client robot process, fused the data, and distributed a new global map to all the robots in the system.

For the 20 minutes that this experiment ran localization for each individual robot was maintained relatively well. The combination of the three robots managed to explore and accurately map more of the test area than a single robot would have been able to in the same amount of time. More importantly, even if a single robot could manage to navigate through the same amount of area that the three robots covered, its mapping accuracy would be much worse than the three-robot system. The longer time required for a single robot to cover the same area as three robots would lead to many more localization errors on the single robot compared to those of any individual robot in the three-robot system.

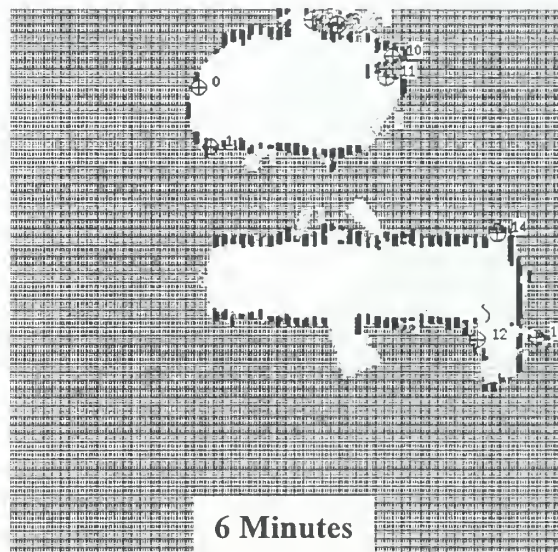
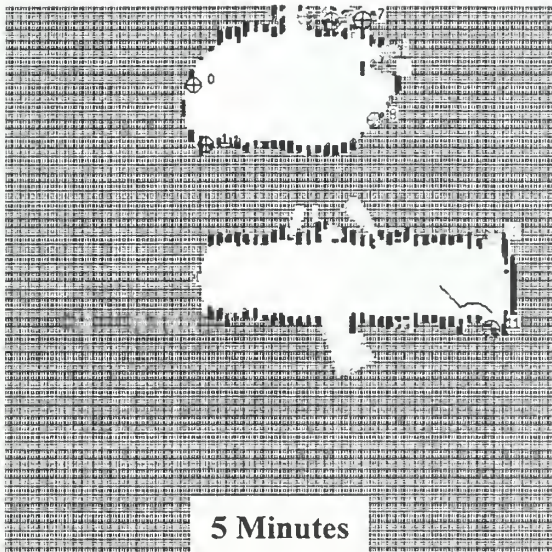
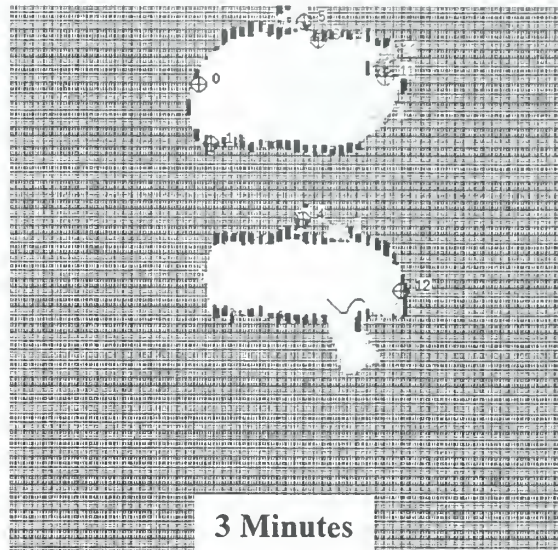
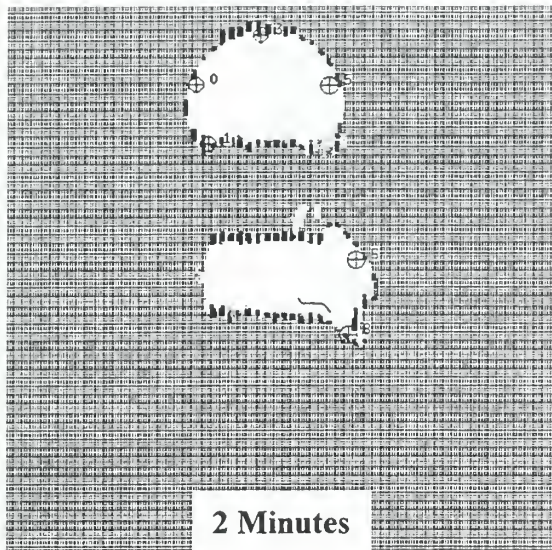


Figure 24. Illustration of a two-robot exploration trial with the robots starting in widely different positions.

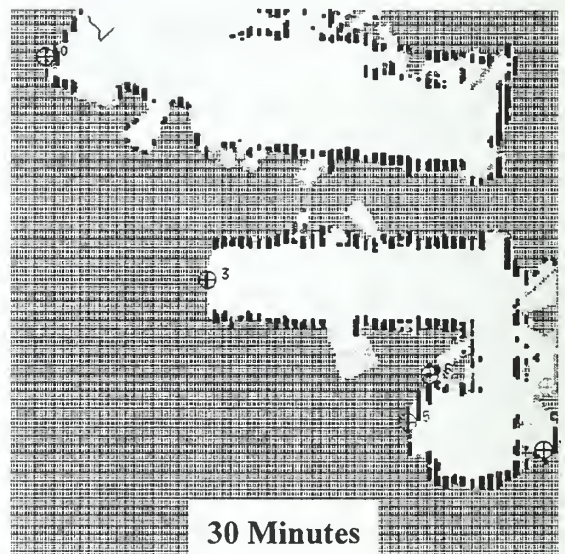
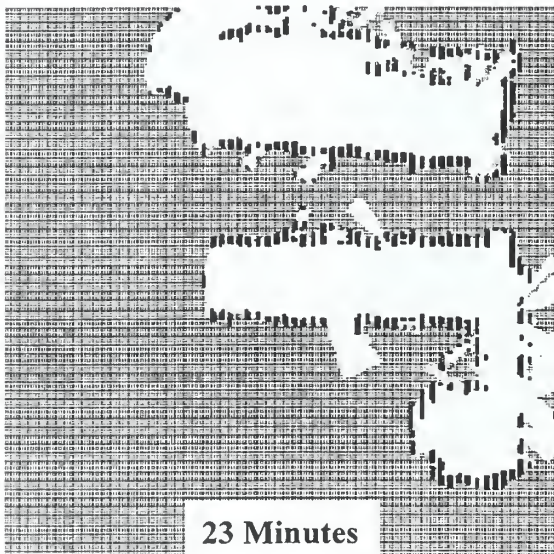
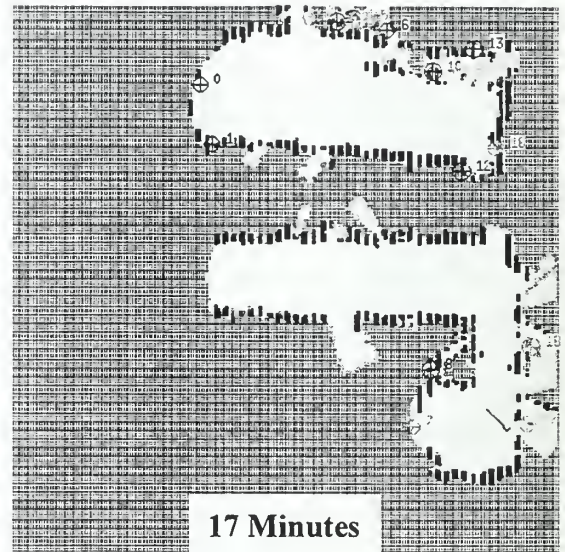
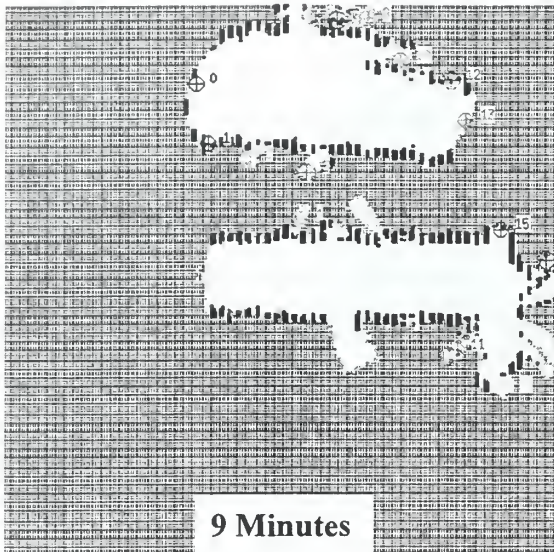


Figure 24 continued. Illustration of a two-robot exploration trial with the robots starting in widely different positions.

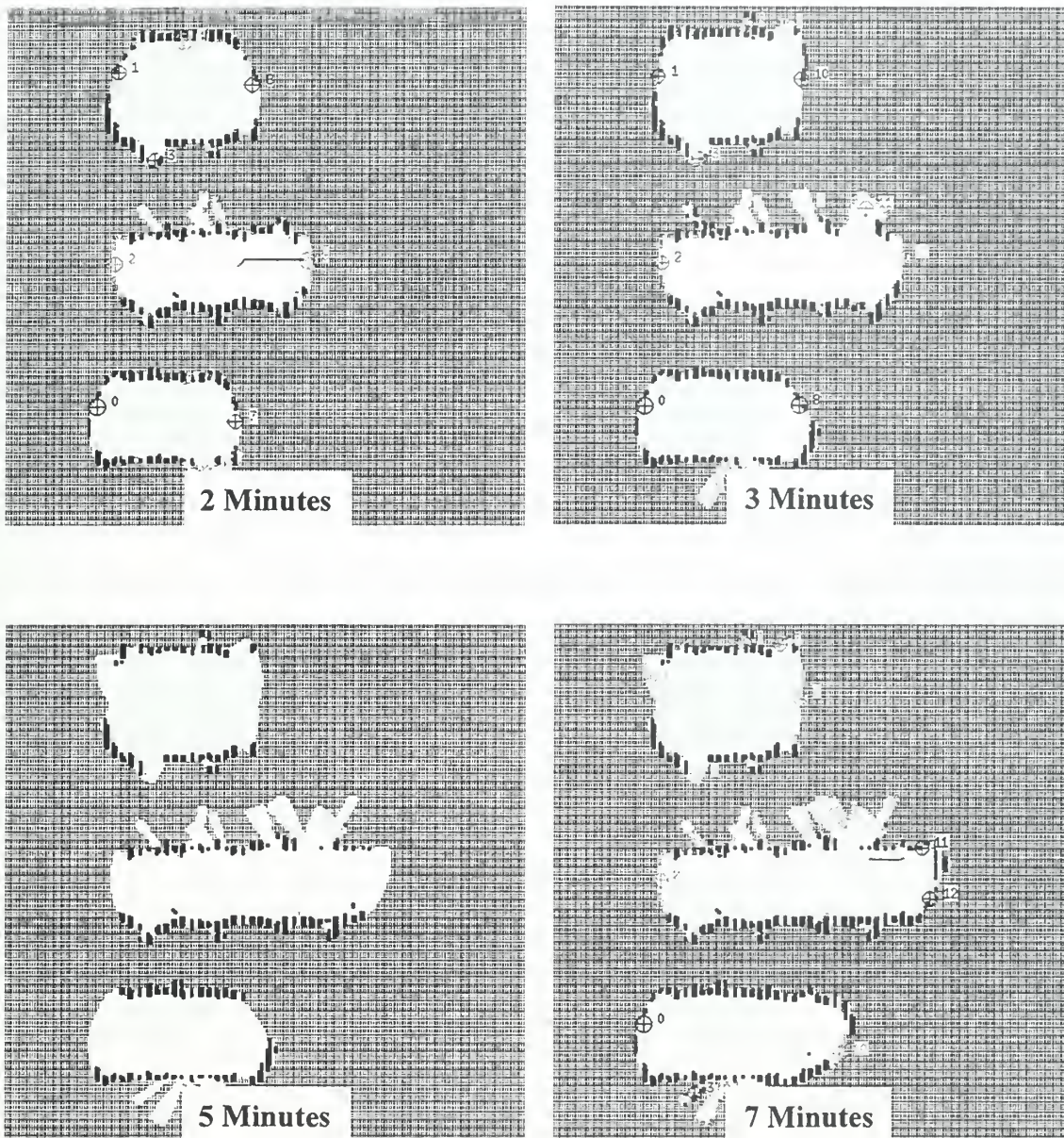


Figure 25. Illustration of a three-robot exploration trial with the robots starting in widely different positions.

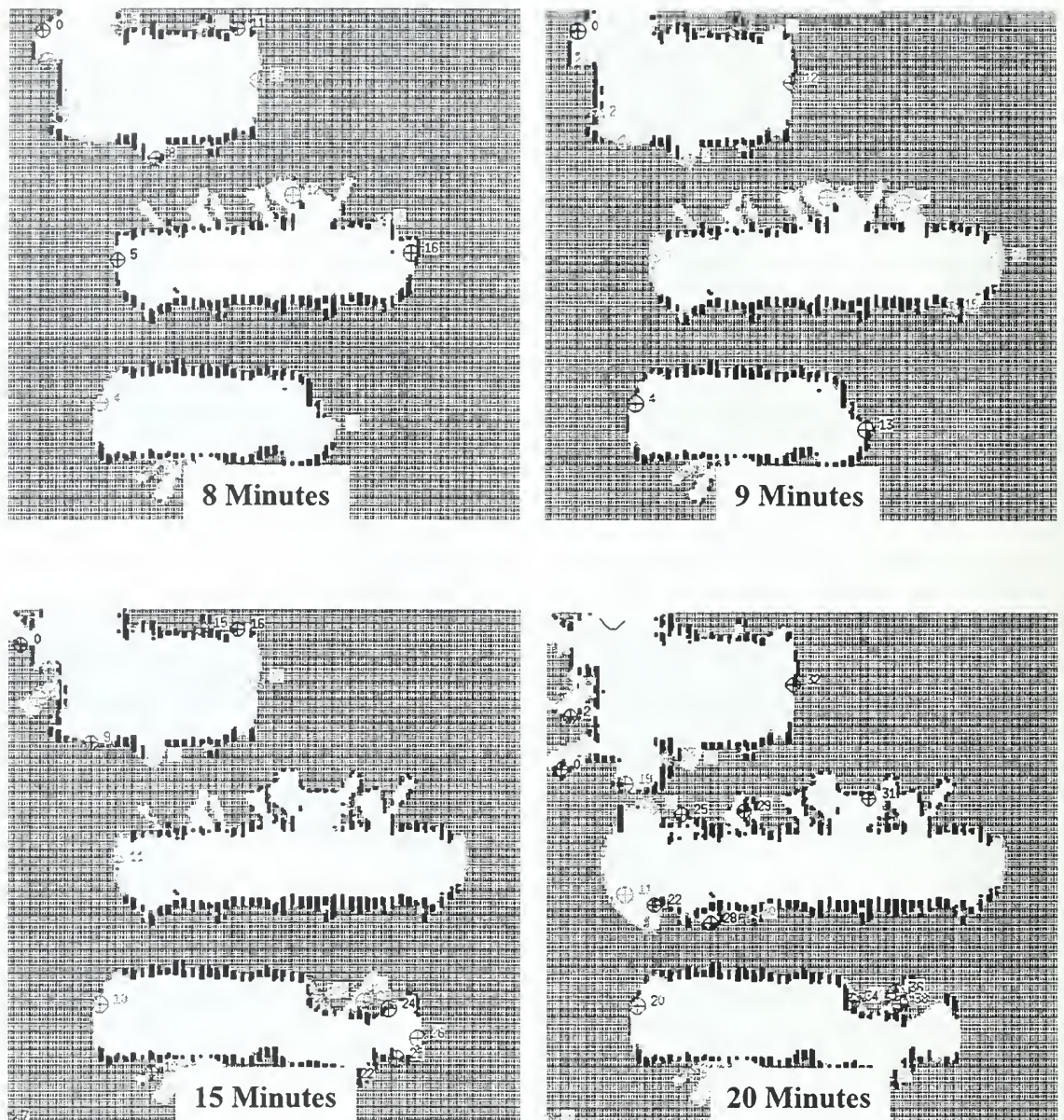


Figure 25 continued. Illustration of a three-robot exploration trial with the robots starting in widely different positions.

4. Counterproductive Effects

Not all the results of using multiple robots were beneficial in terms of mapping accuracy and efficiency. There were several sets of circumstances that often led to multiple robot trials being less efficient than it would be assumed they would be and in

some cases even less efficient than a single robot system. The most common cause of multiple robot inefficiencies was near proximity of one robot to another robot during the exploration and mapping process.

a. “Follow The Leader” Behavior

Two related multiple robot exploration problems came to be known as the “Follow The Leader” and “Dancing Robots” behaviors. Both of these behaviors happen when two or more robots are near (within the trusted sonar range) one another. The “Follow The Leader” behavior can be described as one robot appearing to follow another robot through the test environment and apparently mapping the same area that the leader robot has just mapped. Numerous real-life and simulation trials have revealed two predominant causative factors for this behavior.

The primary cause seems to be the time delay in map data being passed from one robot to another and when that data is processed during the exploration routine. When two robots are near one another they will usually see the same frontiers nearby. Commonly one robot will proceed to a nearby frontier and the other robot will proceed to another nearby frontier that is slightly closer to it. However, if the second robot finishes its exploration of the first frontier and still has not received the map data from the first robot’s exploration there is a good chance that it will travel to the same frontier that the first robot just explored.

The second robot will probably not receive and process the first robot’s map data until after the second robot has already mapped the same area that the first

robot just left. By then the first robot has moved on to a nearby frontier, which is now also the next frontier that the second robot will attempt to explore. This process can continue with the second robot always one set of map data behind the first robot and following it all over the test area.

The other common cause of this behavior is that the second robot senses the first robot that is nearby as an obstacle in the environment with unexplored frontiers around it. While the second robot heads for the first robot's position the second robot moves away to explore a nearby frontier. Once the second robot reaches the first (leader) robot's previous position it makes a sensor sweep, again notes the nearby first robot as an obstacle with new frontiers to explore around it, and again the "Follow The Leader" process continues. In the best case this type of behavior merely reduces the effectiveness of the system by one robot (the following robot). In the worse case, instead of the "Follow The Leader" behavior, the "Dancing Robots" behavior occurs and both robots are rendered ineffective.

b. "Dancing Robots" Behavior

The "Dancing Robots" behavior can be described as two or more robots circling around or moving back and forth near one another for extended period of time and remaining in a relatively small area of the test environment. One variant on this behavior is vaguely reminiscent of the "do-si-do" movement, typically seen in square dancing, where two robots will swap places as if they are swinging each other around. As

interesting as this behavior is to observe, it does not aid in the exploration and mapping process.

This behavior is also caused by a robot sensing another robot as an obstacle with new frontiers around it to be explored. However, in this case both robots sense one another instead of just a follower sensing a leader. Whenever one of them moves to explore the frontiers around the other, the other does the same and thus the robots “dance” around one another. This process can continue indefinitely until one robot is stopped or another nearby frontier that is not caused by a mobile robot is chosen for exploration. Besides keeping two robots from exploring the rest of the area, the constant “dancing” motions have an extremely detrimental effect on localization.

Figure 26 is an example of this inadvertently happening in a three-robot trial. The robots were initially started at positions one, six and seven. Exploration continued normally for the first few minutes. After about 5-7 minutes the robots in the two lower corridors came close enough together to sense one another. At that point many small frontiers were generated by each robot during its exploration process as the other robot moved through the area while the sonar sensor sweep was taking place. The robots began to “dance” around one another for the next 6-7 minutes until one of them was halted. At that point the other robot was able to “break free” because no new frontiers were being generated by a moving robot. However, by this point the robot’s localization has been compromised due to the effects of small movements around the other robot.

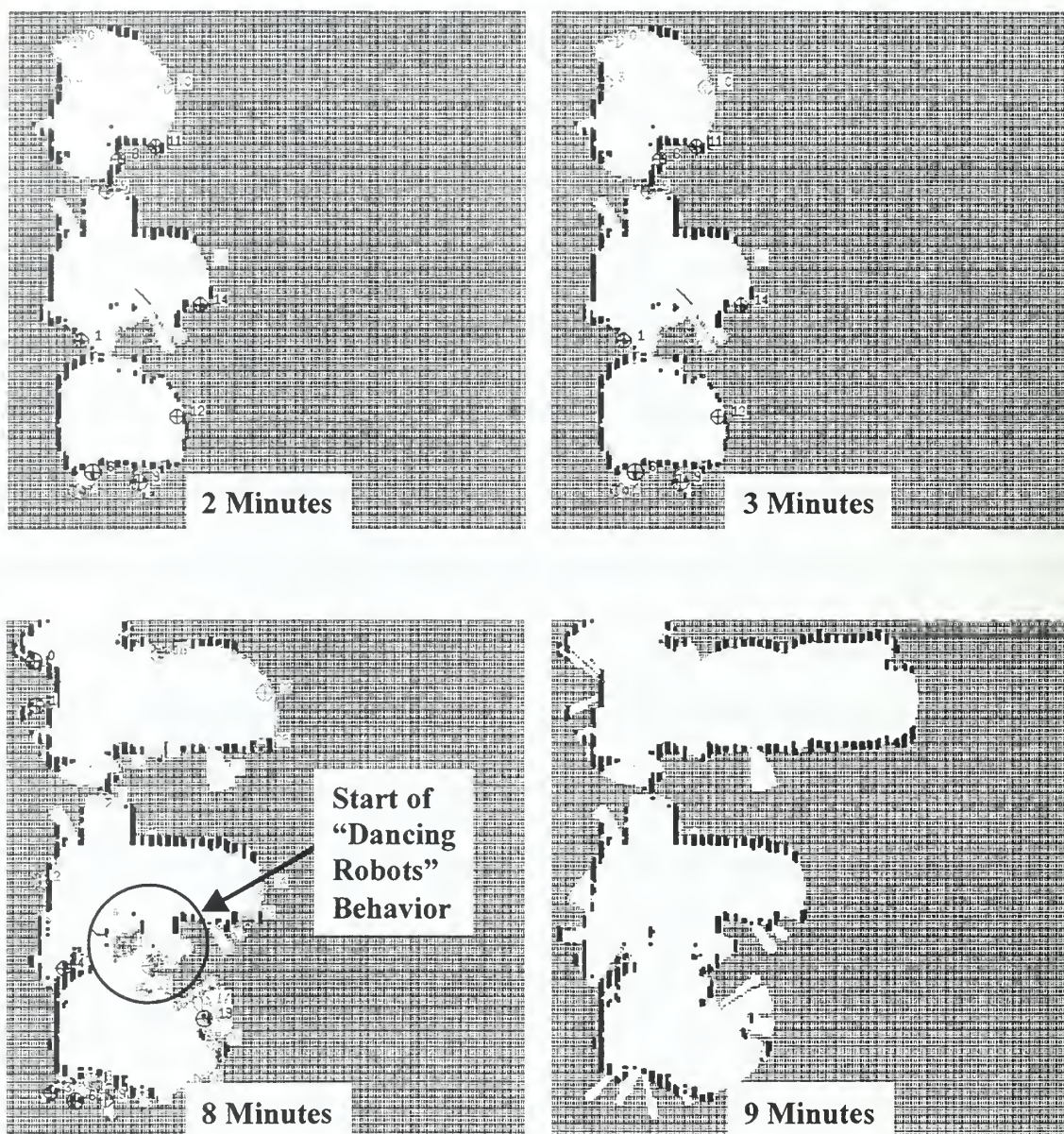


Figure 26. Illustration of “Dancing Robots” behavior during a three-robot trial.

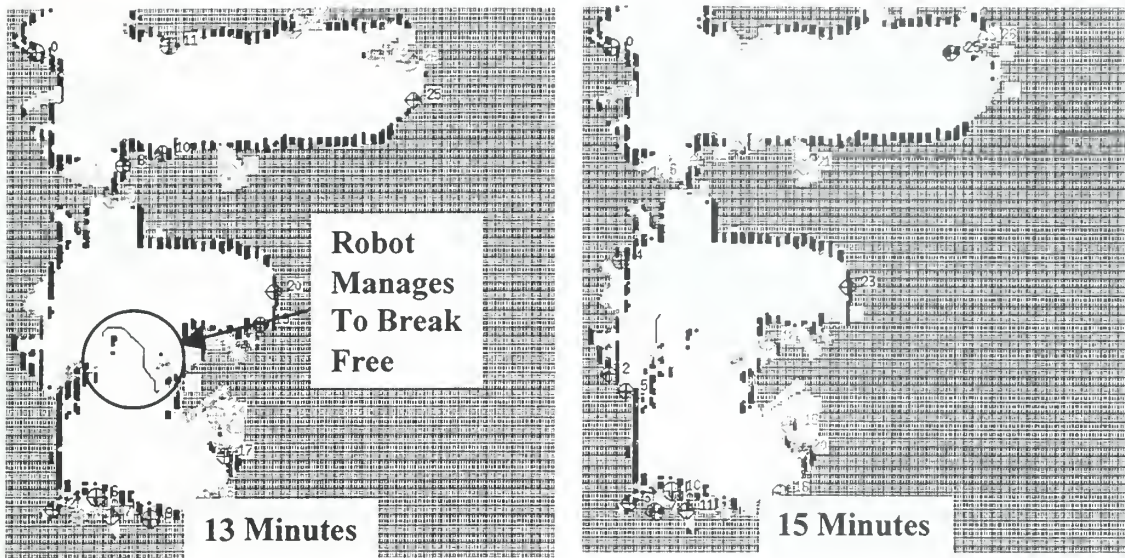
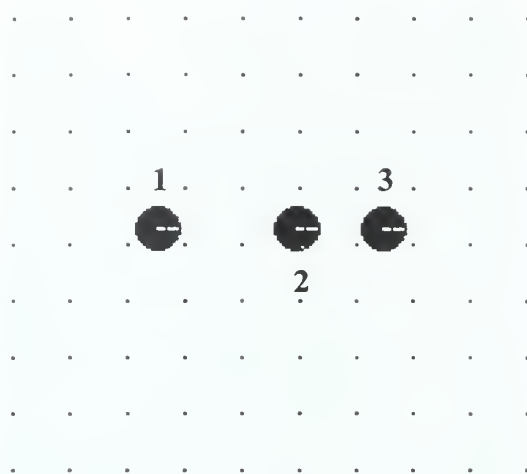


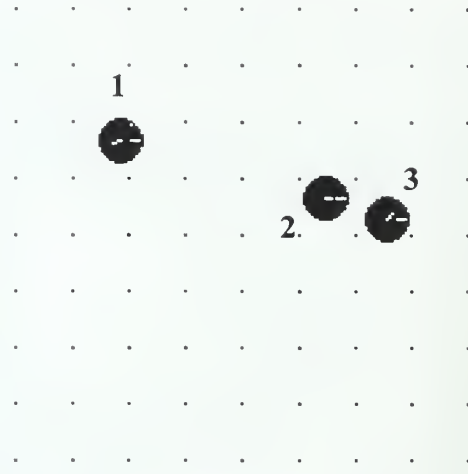
Figure 26 continued. Illustration of “Dancing Robots” behavior during a three-robot trial.

Figure 27 is a trial done with all the robots started in a very near proximity to one another. The initial starting points were positions one, two, and three. *Nserver* can be used to display the robots relative positions in the test environment based on the encoder data sent from the robot back to its respective controlling process. This option was used to track the robots’ positions in the test area. The robots are labeled on the figure for ease of reference.

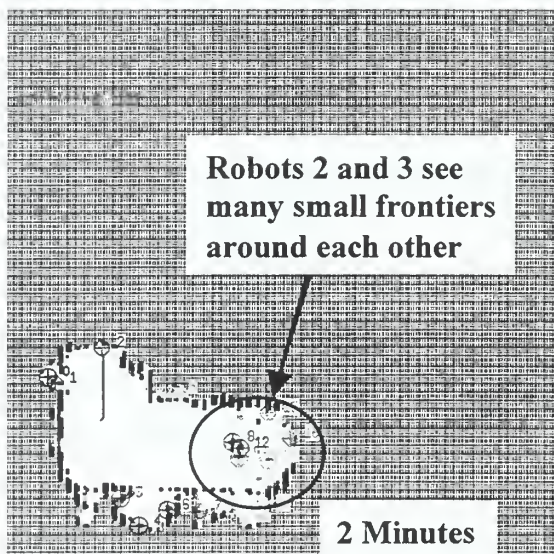
At the start the first robot is slightly farther away from the other robots and does not see any frontiers generated by detecting the other robots as obstacle. In comparison, the second and third robots are much closer together and generate many small frontiers as they detect each other nearby. At first it appeared that the second robot might just follow the third robot, but the third robot detected no frontiers closer than those around the second robot and thus began the “dance.”



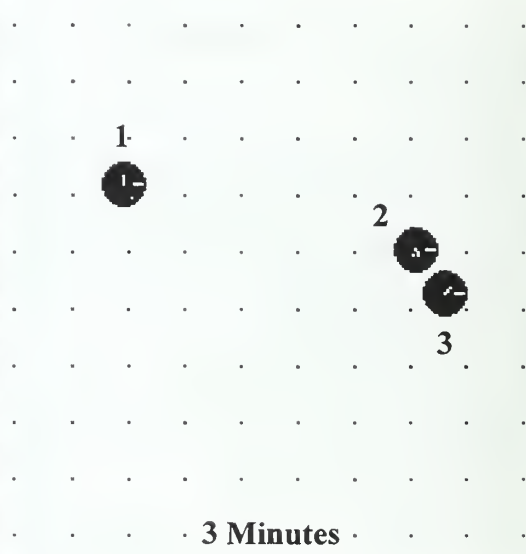
Robots Initial Positions



2 Minutes



2 Minutes



3 Minutes

Figure 27. "Dancing Robot" behavior from robots in near proximity.

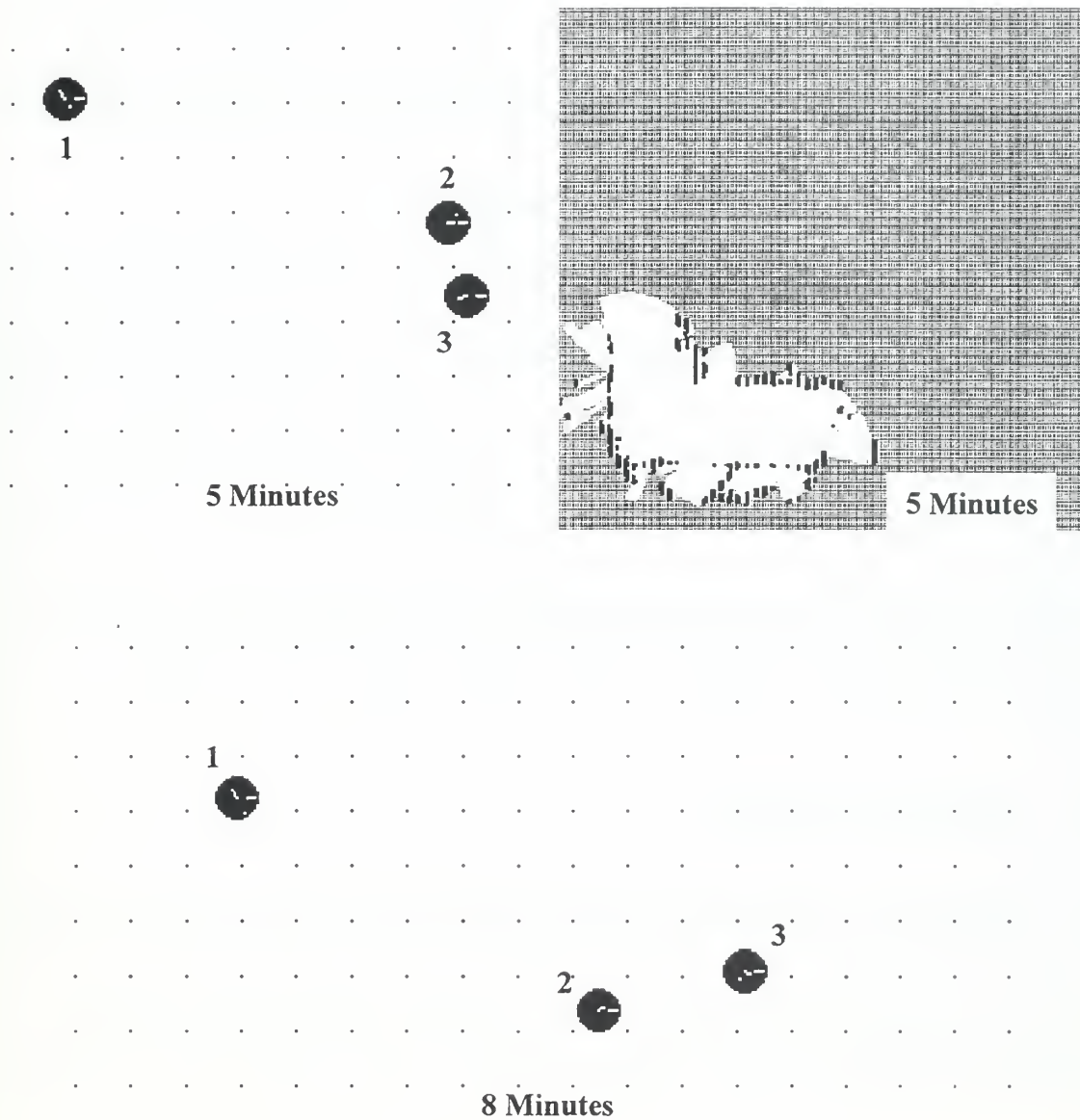


Figure 27 continued. “Dancing Robot” behavior from robots in near proximity.

c. Propagation of “Bad” Data

Throughout all the multiple robot trials it was evident that a single robot could enter “bad” data into the system. Localization reliability varied greatly from robot to robot and trial run to trial run depending on many variable such as the area being mapped, wheel slippage, etc. As seen in many of the multiple robot results shown here a

map made by multiple robots can be very accurate in some areas and very inaccurate in others depending on the varying quality of mapping data sent from the individual robots.

d. Network Reliability Problems

Throughout the trial runs there were unexplained network problems that seemed to increase in severity as the number of robots used was increased. Despite many attempts to track and mitigate the problem they continued to greatly detract from the ability to operate three or more robots for extended periods of time. For three robots 20 minutes was normally the longest time the robots would operate before packet errors caused termination of the experiment. This problem remains under investigation.

C. LESSONS LEARNED

There were several immediate lessons learned from this initial research. The first of these was that rotational odometry errors are much more detrimental to mapping efforts than translational errors. While translational errors do affect the quality of the map the robot is still able to navigate. Rotational odometry errors quickly increase to the point that the robot is completely confused as to which direction it is facing and further navigation becomes impossible. However, any rotational localization scheme (such as wall or corner detection) will probably have a beneficial side effect of aiding translational localization as well.

The second lesson is that the better a robot can explore and map on an individual basis the better it will function as part of a multiple robot exploration and mapping

system. This is basically common sense. Continued improvements in single robot mapping will also improve multiple robot mapping.

The third lesson is that the network reliability issue needs further investigation. It needs to be determined whether the robot trials were causing the problem or if the cause was from an outside source. As mentioned above the local network administrators are currently investigating this problem.

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VII. RECOMMENDATIONS FOR FURTHER STUDY

Due to the extensive amount of software modifications necessary and the constrained equipment availability there were a number of areas of research which promised to be very interesting, but which there was not time to pursue. It is hoped that future students will take up the task of continuing some of the possible avenues mentioned here now that the initial work has been done in order to provide a testbed system for research. These future research possibilities can be broken up into two main categories: those that would involve mainly software modifications only and those that would involve hardware additions or modifications in addition to software changes.

A. SOFTWARE CHANGES ONLY

Many possible research areas would require only software changes to the existing code and require no additional hardware. Also, there is still ample opportunity for optimization of the existing frontier-based exploration routines as currently implemented.

1. Centralized Map Building Process

There are many possible methods to centralize the map building process and possibly reduce or eliminate some of the counterproductive behavior seen in the initial trials while still allowing the individual robot processes to function with relative autonomy. One possibility is to implement a sort of “Blackboard” to which the individual robot processes would write, or send, map information.

The Blackboard would be a separate process or perhaps a “virtual” robot that would only accept local remote maps from all the robots and control no individual robot of its own. It would use the local maps sent to it to build a global map, which could then be sent back to the individual robot processes. It would take the place of the of the first robot process in the current implementation, acting as a server with all the individual robot processes as clients to it. How this might look for a system with four individual robots is illustrated in Figure 28.

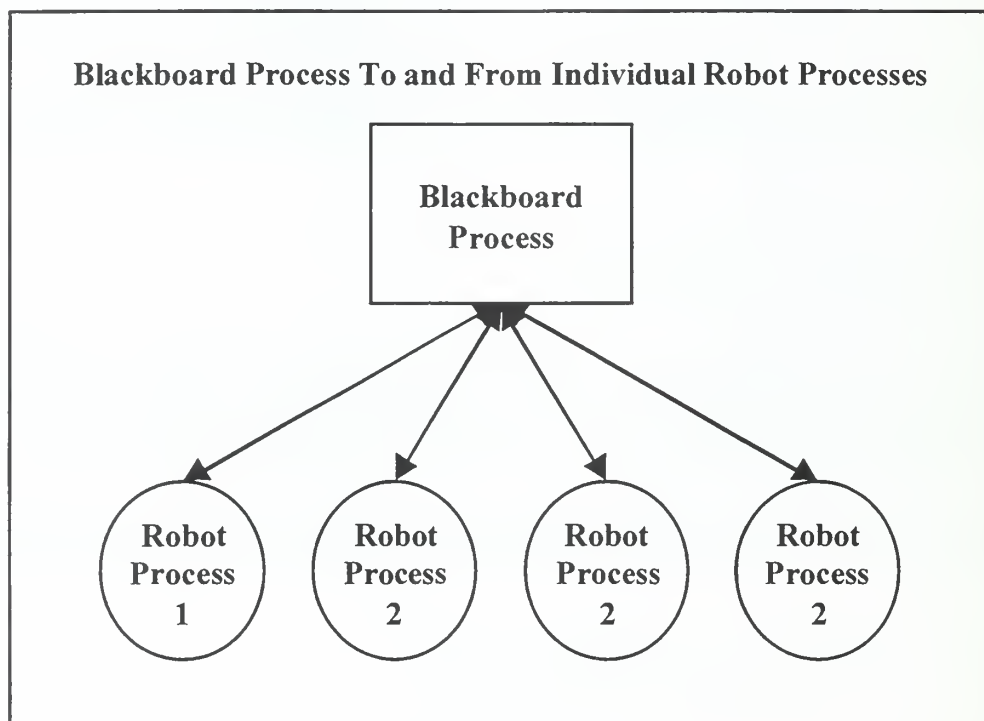


Figure 28. Illustration of a Blackboard-type process interacting with four individual robot processes.

This procedure could have a beneficial effect on the map building process in a number of different ways. By using only local scans to build the global map many of the problems of temporary obstacles gaining persistence and the unwanted reinforcement of “noisy” data are mitigated if not eliminated. Also, since the Blackboard process would

not be controlling a robot directly it can scan the shared memory location or “listen” for new local map messages constantly. This eliminates entirely the problem of missing local updates and losing map information from the individual robots. The Blackboard process would also provide a central point from which a user or operator could monitor the robotic mapping efforts of both the system and individual robots.

The Blackboard process could also be used to track the location of individual robots. Using this information the global map could be marked to either show the area physically covered by a robot as obstacle free or already explored. When this global map is sent back to the individual robots this information could be used to eliminate the problem of robots sensing each other as obstacles and the “dancing robot” behavior that follows. Having the Blackboard process create the global map also makes for a convenient location for any new robots joining the system to find out the most current map and avoid duplication of earlier efforts. More of the challenges of managing a dynamic robot population are discussed below.

The basics of the Blackboard process should actually require very little coding. Most of the functionality of taking in local maps and creating a global map is already done in the current implementation by the first robot process when acting as a server. Also, the client robot processes already write their local maps to and read the global map from the same shared memory location. For a basic Blackboard process simply removing the code that controls an individual robot from the original robot code and having the process constantly scan for and process local maps from the client processes would be sufficient.

2. Centrally Coordinated Effort

Another aspect that is worth investigating is removing some autonomy from the individual robot processes and creating some sort of centralized control or supervisory function. In this case the supervisory process would be able to direct or at least influence the individual robots' actions. This control could be constant, thus removing all autonomy from the individual robot processes, or on an as needed or exceptional basis, otherwise allowing the robots to act independently.

This control process would most likely act in conjunction with some sort of robot tracking process, perhaps one much like the Blackboard process described above. Besides eliminating the "Dancing Robots" and "Follow The Leader" behaviors it would also provide a single point from which an outside user or operator could direct the actions of an individual or groups of robots as well as see the results of the robotic mapping efforts. This is an important option in a deployable reconnaissance system.

This modification of the original implementation would require more extensive changes than just adding a simple tracking system. Besides the creating the supervisory process itself, it would also be necessary to make extensive modifications to the individual robot processes to have them accept commands from an outside source.

3. Dynamic Robot Population

The current implementation does not allow for an easy or simple method of joining additional robots to the system after initialization or for a way for a robot to

gracefully leave the system (say to go on to another task or report for maintenance).

What is needed is some way to easily manage a dynamic or changing robot population.

Whenever a robot enters the system it needs some sort of unique identifier within the system so that other robots and any supervisory or other processes that exist have a way to identify or track the new robot. This identifier also serves to identify any local maps made by the robot. Under the current implementation the robot identifier is assigned by the *Nserver* in the order that the robots are created in the program. The user then assigns the individual robot processes a number corresponding to the one given by the *Nserver* program. For a dynamic robot population a dynamic method of allocating unique identifiers to robots is required.

One possibility would be to use a simple Boolean array stored in the shared memory location used by all the robots. The size of the array would be the maximum number of robots that the system could manage. The array would be initialized to all zeros representing no robots in the system. As robots enter the system they would first scan the array until they found the first zero position. The robot would set the zero to a one and the numeric position in the array of that zero would become the robot's unique identifier.

Likewise, a robot leaving the system would reset its identifier position in the array to a zero, thus opening up that identifier for a new robot joining the system to use. If the system is filled with all the robots it can use or manage new robots would find the array filled with ones and would act appropriately depending on the system design, either waiting until an opening is available, moving on, or taking some other action altogether.

How this might function for a system with a maximum capacity of four robots is illustrated in Figure 29.

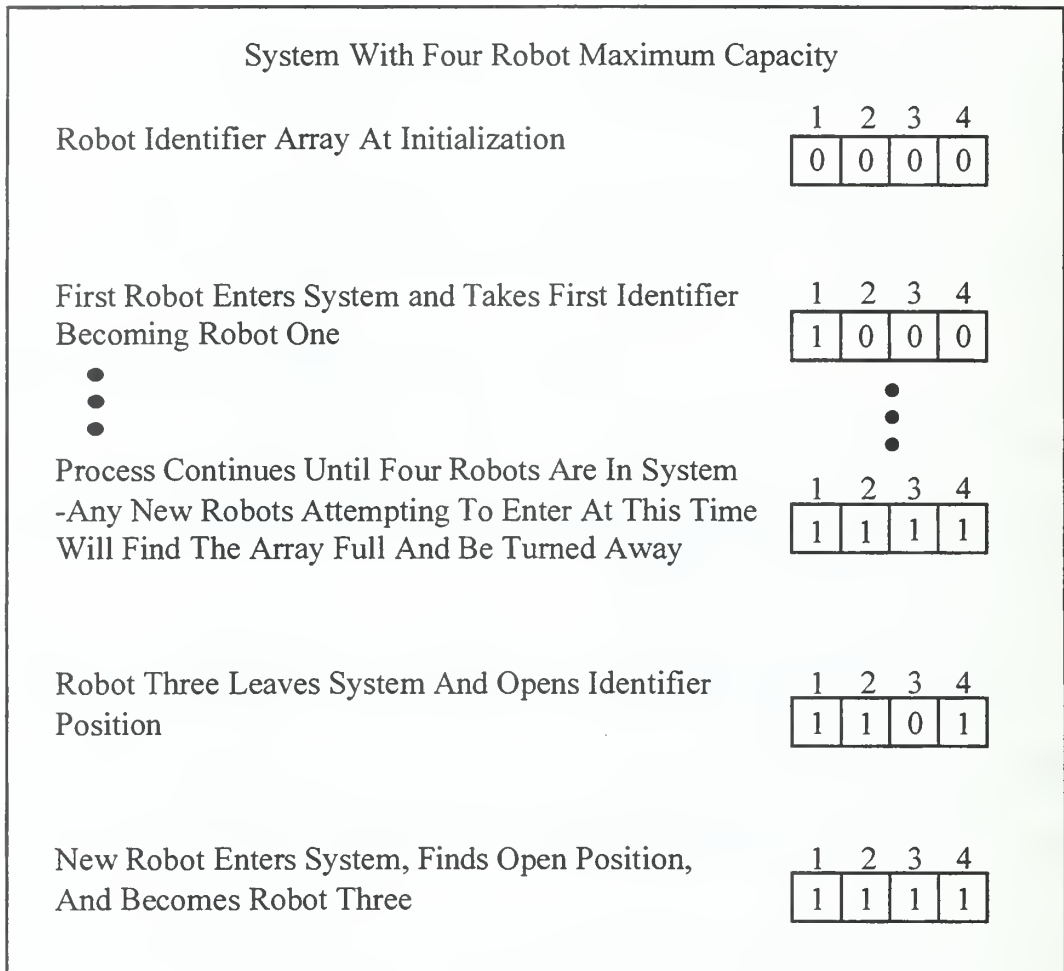


Figure 29. Illustration of the use of a Robot Identifier Array in the managing of a system with a four robot limit.

Furthermore, this array could hold other information rather than just the individual robot identifier data. In conjunction with the sort of supervisory process described above it might also be useful to have additional information such as sensor types and ranges available on the robot, mobility platform capabilities and limitations, and other types of data that could aid the central controlling process in managing the robotic resources available to it.

4. Communications Networking Model

The communications model in the current implementation is based on a point-to-point system in which an individual robot process explicitly communicates with only one other robot process at a time across a hardwired network connection. To better simulate a deployable system, where all links are wireless, a broadcast communications model should be used. One possibility would be to simulate the effects of range loss by including the individual robot's coordinates in the global map as an attachment to any message. The receiving robot could compare the sending robot's location to its own and decide whether or not to "accept" the message based on the distance between the two robots.

Another area worth further research is the general appropriateness of TCP as a communications protocol for mobile robot systems. Mobile robots in a real world wireless environment do not fit well with the design behind of TCP and its orientation around continuous streams of data. Mobile robots require a more message-based communications design. There are a number of other possible networking models and protocols other than the TCP/IP model currently used. Some work in this area has already been done, focusing in on the use of the User Datagram Protocol. [Ref. 33]

5. Improved Localization Method

As has already been mentioned the current implementation has no method of localization beyond simple dead reckoning using the robot's on-board odometric systems.

As shown in Chapter VI, this quickly proves insufficient as a means to accurately track the robot's location and map making efforts suffer accordingly. There has already been much work done with localization routines on a NOMAD 200 robot at NRL, both alone and in conjunction with frontier-based exploration [Ref. 20, 22]. It is hoped that their methods might be adapted to work with the NOMAD SCOUT robot as well.

Other research at NPS has concentrated on determining a robot's location in the real world through interpretation of its surroundings [Ref. 8, 9]. This work also shows promise of forming the basis of a general localization routine for any number or type of mobile robots. Other efforts have attempted to have the robot match its current surroundings to an evidence grid built by the robot and correct any rotational or translational errors that may have developed [Ref. 34].

Another possibility involves the outside use of some sort of supervisory process such as described above. This process could monitor a robot's self-reported location, the robot's reported surrounding, as well as any sensor reports from other robot's in the area. Using this information the supervisory process might track each of the robots in the system and send correction information to them as their dead reckoning systems begin to drift. Still another possibility is a group of robots forming a local reference system without the use of any central process. Some work has already been done in this area [Ref. 35].

6. Managing a Heterogeneous Robot Population

The multiple robot frontier-based exploration system has been implemented separately on groups of NOMAD 200 and NOMAD SCOUT robots. So far there has been no work done on integrating a heterogeneous population of robots in such a system. There are important questions concerning the code base for such a system. Would it be better (or even feasible) to write a single set of code that would adequately work with the varying sensor systems and mobility features of each platform? Or would it be better to have two completely different sets of routines for each type of robot?

An interesting aspect of a heterogeneous population of robots is the varying capabilities of each type of robot. While the NOMAD 200 has a more precise positioning capability, the NOMAD SCOUT is somewhat smaller and may be able to explore spaces the NOMAD 200 cannot reach. It would be interesting to find a way to use the diversity of the robot types as an advantage in accurate and complete exploration and map making. Both NRL and NPS now have both types of robots, thus providing a basis for such work. Some theoretical work has already been done in this area [Ref. 36].

7. Identifying System Tradeoffs

Initial research has already identified some of the tradeoffs of optimizing or adjusting various aspects of the system. For instance, reducing the “trustworthy” sonar range results in much less problems with specular reflections, but increases the total distance a robot or number of robots must travel in order to map a given area. This

increased travel distance, especially the larger number of small movements necessary to sweep the sonar sensors at new frontiers, leads to increased odometry error. On the other hand, increasing the “trusted” sonar range reduces travel requirements, but causes a corresponding increase in false sonar returns.

Much more study is needed on optimizing the sensor model for the best combination of accurate mapping with minimal movement. Of course an adequate localization routine would solve many problems, but even with a good localization routine minimizing travel distances would be beneficial to the overall system. Other possible tradeoff studies include autonomy versus centralized control and heterogeneous versus homogeneous robot populations. Some work has already been done in the study of the interaction between quantity of robots in a system, sensor quality, and mobility constraints on system performance for a given mission [Ref. 37].

8. Modified Movement Behaviors

The original movement behaviors for the robot in the routine *robot.cc* were written with the capabilities of the NOMAD 200 robot in mind. Problems arise with using these same behaviors on the NOMAD SCOUT robot. While the NOMAD 200 can translate on its own axis, the NOMAD SCOUT cannot. Therefore movement behaviors that would have been simple rotations or shallow arcs on a NOMAD 200 become much larger movements when the conversion macros interpret them for use on the NOMAD SCOUT.

This causes many difficulties when the NOMAD SCOUT is near to and facing a wall or other obstacle at the end of a sensor sweep. When the robot tries to move on to a

new frontier the macro translates the current movement commands into a forward turning motion. If the robot is too close to the wall it will be blocked and eventually the new frontier it should have traveled to will be marked as inaccessible. Some type of backing up or modified turn behavior would seem to be a possible solution.

Other opportunities also exist to counter the “Follow The Leader” and “Dancing Robot” behaviors. One possible solution to be explored might be to have the robot broadcast its location either to all robots in the system or at least those nearby. That way a robot could recognize that the obstacle it is trying to map is in fact another robot. Of course any sort of centralized supervisory process could also counter this problem very easily. Another possibility is to set some sort of limit on how long a robot would continue to map a small area despite new frontiers constantly appearing in that area. After a period of time it could give up and move on to a radically different geographical area.

B. HARDWARE AND SOFTWARE CHANGES

Other possible research areas would require additional hardware and/or modification of the already existing hardware in the system. In addition, software modifications would be necessary in order to use the added or changed hardware. Some of the hardware for the research possibilities mentioned below is already available at NPS.

1. Human – Robotic System Interaction

The area of real-time human-robotic interaction holds many, many possible research opportunities. In the current implementation the current map is displayed on a workstation and the opportunities for user interaction are very limited. Obviously, for a practical, deployable system these limitations must be removed.

There is a need for some sort of portable system through which a user can receive information from a single robot or groups of robots and also direct the actions of an individual robot or number of robots. Ideally, the device would be lightweight, unobtrusive, and user friendly in design and use. While earlier research had focused on rather large control and display systems [Ref. 38], perhaps the best model available today for such a device is the in the form factor and design of a Personal Digital Assistant (PDA).

There are a number of different types of PDAs available for research at NPS. Many of them have some type of wireless connection or network capability. What is required is a method for a map data to be transmitted to these devices in a useable format and some method for operator commands to be sent back to the network and then on to the robot(s). Once this is possible many other research opportunities become available. What is the best way to manage the system from the operator point-of-view? For a deployed system, how much control does the operator need or even want? Is controlling the robot(s) the operator's primary duty or something that should be done on an as-required basis? What are the possibilities for cooperative exploration of an area between

human and robot? How best should the system signal the operator to possible danger areas or other areas of interest? These and other questions should be investigated early before large amounts of funding are spent on programs that later are found to be unworkable or impractical to implement.

2. Outdoor Trials

Any practical, field deployable system will need to work outdoors as well indoors. Even if the system is build primarily for mapping the interiors of buildings the individual robots will most likely have to traverse rough, broken, urban terrain to travel from one operating site to another. Neither the NOMAD 200 nor the NOMAD SCOUT has much capability in this regard as currently configured. At this time their manufacturer has no announced plans to market any outdoor-capable models either.

However, there does exist other outdoor-capable robotic systems at NPS. In particular the “Shepherd” vehicle [Ref. 39, 40], under cooperative development by several different departments at NPS, is a robot with a four-wheeled all-terrain-vehicle (ATV) style chassis with independent driving and steering capability. Much study has been conducted on this platform concerning motion control and localization via inertial sensors and the use of a Global Positioning System (GPS) receiver. It would seem that integrating some sort of mapping capability into it would be a natural next step. There are many questions about how much of the current implementation of the frontier-based exploration code could be ported to the new platform, but the fundamentals of the process would seem to remain the same.

3. Removing Dependency on Wired Network

Perhaps one of the most ambitious possibilities is removing the dependency that the current implementation has on a wired network to provide communications connectivity. The NOMAD SCOUT has the capability to be completely independent through the use of a laptop computer running the LINUX operating system. A laptop can be mounted on top of the NOMAD SCOUT and can run the same code locally (after it is recompiled) that is currently run on a remote Sun workstation.

Once the NOMAD SCOUT robots are operating independently of a wired network it might be possible to better implement a broadcast model of communication amongst the robots. The wireless modems used in the current implementation are capable of serving as either point-to-point communications stations or as part of a distributed system. Because there would no longer be a shared memory location, the exploration and mapping software would have to be modified to actually send all the map data and not just a pointer to the data or message that it is available to the other robots in the system. There is already a body of work supporting communications protocols for distributed robotic systems without a centralized communications server [Ref. 41].

4. Additional Sensor Systems

Using laptops on the NOMAD SCOUT robots as mentioned above also opens up the opportunity to integrate additional sensor systems on the platform. The unused input ports of the laptop provide a means to include video, audio, or any of a number of

other sensing devices to the system. In addition, there is also the possibility of adding a means of detecting beacons in the environment or on other robots as an aid to navigation and localization.

VIII. CONCLUSIONS

Oftentimes the hardest part of any journey is just getting started. This thesis and the research involved in creating it have been aimed at creating a starting point for future studies. Now that the basics of a real world (as compared to simulated) multiple robot system has been developed and implemented at NPS, a huge number of additional avenues of investigation are available.

It has been shown that much work remains in order to create a consistent and robust exploration and mapping system before many of the questions surrounding robotic battlefield support can be answered. However, now there exists at NPS a “critical mass” of mobile robot types with varying capabilities and at least basic software to enable some of them to operate in a shared real-world environment toward a common goal.

Many of the problems encountered in this research are very similar to those discovered by other researchers when moving a robotic system from one environment to another [Ref. 42]. In the case of this research the testing of multiple mobile robots has been moved from simulation-only environment to a combination of simulation and real-world testing. This transition has revealed many details of multiple robotic systems that otherwise would have remained hidden in simulator-only testing.

In Chapter VI there are listed many possible areas of study based on the work presented here. These are just the start of many possible thesis opportunities involving hardware, software, human-machine interaction, etc. One of the most exciting and challenging things about robotics as a field of study is the number of different fields and

disciplines that it encompasses. It is hoped that future students will take up this challenge and carry on the work started here.

APPENDIX A. SOURCE CODE FOR COLLECTION OF SIMPLE SENSOR RETURN DATA

This appendix contains the source code that was used to collect sonar range data on early map making efforts with the NOMAD SCOUT robot.

```
1  /*****
2  *
3  * PROGRAM: world_sonar.c
4  *
5  * PURPOSE: To collect sonar data for establishing a world map.
6  * modified for Scout by Patrick A. Hillmeyer
7  *****/
8
9
10 /*** Include Files ***/
11
12 #include "Nclient.h"
13 #include <stdio.h>
14 #include <stdlib.h>
15 #include <math.h>
16
17
18
19 /*** Conversion MACROS courtesy of Nomadic Inc   ***/
20 /** original beta macros for SCOUT models *****/
21
22 #define RIGHT(trans, steer)  (trans + (int)((float)steer*368.61/3600.0))
23 #define LEFT(trans, steer)   (trans - (int)((float)steer*368.61/3600.0))
24
25 #define scout_vm(trans, steer)  vm(RIGHT(trans, steer), LEFT(trans,
26 steer), 0)
27 #define scout_pr(trans, steer)  pr(RIGHT(trans, steer), LEFT(trans,
28 steer), 0)
29
30
31
32
33 /*** Function Prototypes ***/
34
35 void GetSensorData(void);
36
37
38 /*** Globals ***/
39
40 long SonarRange[16]; /* array of sonar readings (inches) */
41 long IRRange[16]; /* array of infrared readings (no units) */
42 long robot_config[4];
43
44 /*** Main Program ***/
45
46 main (unsigned int argc, char** argv)
47 {
48     int i, j, index;
49     int order[16];
50     FILE *fp;
51
```

```

52  /* Connect to Nserver. The parameter passed must always be 1. */
53  connect_robot(1, MODEL_SCOUT, "scout1.ece.nps.navy.mil", 4001);
54
55
56  /* Initialize Smask and send to robot. Smask is a large array that
57  controls which data the robot returns back to the server. This
58  function tells the robot to give us everything. */
59  init_mask();
60
61
62  /* Configure timeout (given in seconds). This is how long the robot
63  will keep moving if you become disconnected. Set this low if there
64  are walls nearby. */
65  conf_tm(1);
66
67
68  /* Sonar setup */
69  for (i = 0; i < 16; i++)
70      order[i] = i;
71  conf_sn(15, order);
72
73
74  zr(); /* tell robot to zero itself */
75
76
77
78  fp = fopen("range.dat", "w");
79
80  /* Main loop. */
81  for (i=0; i<2; i++)
82  {
83      GetSensorData();
84
85      for (j=0; j<16; j++)
86          fprintf(fp, "%8d %8d %8d %8d %8d \n",
87                  robot_config[ 0], robot_config[ 1], robot_config[ 2],
88                  robot_config[ 3],
89                  SonarRange[ j] );
90  }
91
92  fclose(fp);
93
94  /* Disconnect. */
95  disconnect_robot(1);
96 }
97
98
99
100 /* GetSensorData(). Read in sensor data and load into arrays. */
101 void GetSensorData (void)
102 {
103     int i;
104
105
106     /* Read all sensors and load data into State array. */
107     gs();
108
109

```



```

110  /* Read State array data and put readings into individual arrays. */
111  for (i = 0; i < 16; i++)
112  {
113      /* Sonar ranges are given in inches, and can be between 6 and
114      255, inclusive. */
115      SonarRange[i] = State[17+i];
116
117      /* IR readings are between 0 and 15, inclusive. This value is
118      inversely proportional to the light reflected by the detected
119      object, and is thus proportional to the distance of the
120      object. Due to the many environmental variables effecting the
121      reflectance of infrared light, distances cannot be accurately
122      ascribed to the IR readings. */
123      IRRange[i] = State[1+i];
124  }
125
126  for (i = 0; i < 4; i++)
127      robot_config[i] = State[34+i];
128
129  }

```

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97
98
99
100

1. The first part of the document is a letter from the President of the United States to the Congress, dated January 1, 1861. It is a very important document, as it sets out the President's policy for the new year. The President states that he is pleased to see the Congress assembled, and that he is confident that the country is in a state of peace and prosperity. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging. The President then goes on to discuss the state of the country, and the progress of the government. He mentions that the country is in a state of peace and prosperity, and that the government is working hard to improve the lives of the people. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging. The President then goes on to discuss the state of the country, and the progress of the government. He mentions that the country is in a state of peace and prosperity, and that the government is working hard to improve the lives of the people. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging.

2. The second part of the document is a letter from the President of the United States to the Congress, dated January 1, 1861. It is a very important document, as it sets out the President's policy for the new year. The President states that he is pleased to see the Congress assembled, and that he is confident that the country is in a state of peace and prosperity. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging. The President then goes on to discuss the state of the country, and the progress of the government. He mentions that the country is in a state of peace and prosperity, and that the government is working hard to improve the lives of the people. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging. The President then goes on to discuss the state of the country, and the progress of the government. He mentions that the country is in a state of peace and prosperity, and that the government is working hard to improve the lives of the people. He also mentions that he has received many letters from the people, and that they are all very kind and encouraging.

APPENDIX B. MATLAB SOURCE CODE FOR PLOTTING OF SIMPLE SENSOR RETURN DATA

This appendix contains the MATLAB M-file that was used to analyze and display the sonar range data from early map making efforts with the NOMAD SCOUT robot.

```
1  % Capt Patrick A. Hillmeyer, USMC
2  % Code originally written for EC 4300 Robotics class
3  % Written to interpret sonar range data collected
4  % from a NOMAD SCOUT robot
5
6  % Load the range data collected during the robot's travel
7  load rangel.dat
8
9  robo_data=rangel;
10
11 % Convert robot x,y coordinates to inches
12 rob_x_in_world=robo_data(:,1)/10;
13 rob_y_in_world=robo_data(:,2)/10;
14
15 % In this data the base and turret are aligned
16 % therefore no alignment correction is necessary
17 % Carryover from old NOMAD 200 version of code
18
19 % covert angles to degrees then to radians
20 base_angle=(robo_data(:,3)/10)*pi/180;
21 obj_dist_fr_rob=robo_data(:,5);
22
23 num_sensors=16;
24 deg_per_sensor=360/num_sensors;
25 rad_per_sensor=deg_per_sensor*pi/180;
26
27 % correct for sensor location offset
28 % from robot center
29 rob_radius=8.81;
30
31 % Set the range at which to trust the
32 % sonar data
33 s_trust=60;
34
35 % plot robot path alone
36 figure(1)
37 plot(rob_x_in_world,rob_y_in_world,'w.')
38 title('Robot path in real (or simulated) world')
39 xlabel('Inches'),ylabel('Inches')
40 axis('equal')
41
42 % now plot sonar hits as robot moved
43 x_sonar_hits=[];
44 y_sonar_hits=[];
45
46 % Read through the data in sets corresponding
47 % to the number of sensor readings taken at each
48 % location in the robot's path
49 for ctr2=0:(length(robo_data)/num_sensors)-1
50
51     for ctr3=1:num_sensors
```

```

52
53     abs_data_pt=(num_sensors*ctr2)+ctr3;
54
55     % only process if valid reading
56     if obj_dist_fr_rob(abs_data_pt)<s_trust
57
58         A_B_T=[ cos(base_angle(abs_data_pt)) ...
59                -sin(base_angle(abs_data_pt)) ...
60                0 rob_x_in_world(abs_data_pt);
61                sin(base_angle(abs_data_pt)) ...
62                cos(base_angle(abs_data_pt)) ...
63                0 rob_y_in_world(abs_data_pt);
64                0 0 1 0;
65                0 0 0 1];
66
67         % correct for off-by-one discrepancy
68         % in sensor numbering
69         sensor_num=ctr3-1;
70
71         B_P=[ (obj_dist_fr_rob(abs_data_pt)+rob_radius) ...
72              *cos(sensor_num*rad_per_sensor);
73              (obj_dist_fr_rob(abs_data_pt)+rob_radius) ...
74              *sin(sensor_num*rad_per_sensor);
75              0;
76              1];
77
78         A_P=A_B_T*B_P;
79
80         x_sonar_hits=[ x_sonar_hits A_P(1)];
81         y_sonar_hits=[ y_sonar_hits A_P(2)];
82
83     end % end for if
84
85 end % end for ctr3
86
87 end % end for ctr2
88
89 figure(2)
90 plot(x_sonar_hits,y_sonar_hits,'w.', ...
91      rob_x_in_world,rob_y_in_world,'w.')
92 title('Simulated world sonar data - 60 inch sonar reliability')
93 xlabel('Inches'),ylabel('Inches')
94 axis('equal')

```

APPENDIX C. FRONTIER-BASED EXPLORATION CODE – GRID.H

This appendix contains the header file for the routine that builds the evidence grid based on the sensor return data.

```
1  /*
2
3  grid.h
4
5  Header file for robot/evidence grid functions
6  original code by Brian Yamauchi
7
8  Modifications for SCOUT THESIS
9  by Patrick A. Hillmeyer
10
11 */
12
13 #include "cmacs.h"
14 #include "volsense.h"
15
16 /* Grid occupied threshold */
17
18 #define GRID_POS_THRESH 16
19
20 /* Grid unoccupied threshold */
21
22 #define GRID_NEG_THRESH -16
23
24 /* Local Grid dimensions (feet) */
25
26 /* BEGIN SCOUT THESIS CHANGE */
27 /* change the local grid dimensions to match the global grid dimensions
28 */
29 #define X_MIN -22.0
30 #define X_MAX 22.0
31 #define Y_MIN -22.0
32 #define Y_MAX 22.0
33 #define Z_MIN 0.0
34 #define Z_MAX 5.0
35
36 /* Grid resolution (cells) */
37 /* increase the number of cells */
38 /* the value here has to be a power of 2 and symmetrical */
39 /* i.e 64 by 64, 128 by 128, etc */
40 /* this is true for all the other grid resolutions below as well */
41
42 #define X_RES 256
43 #define Y_RES 256
44 #define Z_RES 1
45
46 /* END SCOUT THESIS CHANGE */
47
48
49 /* Global grid dimensions (feet) */
50
51 #define GLOBAL_X_MIN -22.0
52 #define GLOBAL_X_MAX 22.0
```



```

53 #define GLOBAL_Y_MIN -22.0
54 #define GLOBAL_Y_MAX 22.0
55 #define GLOBAL_Z_MIN 0.0
56 #define GLOBAL_Z_MAX 5.0
57
58
59
60 /* Global grid resolution (cells) */
61
62 #define GLOBAL_X_RES 256
63 #define GLOBAL_Y_RES 256
64 #define GLOBAL_Z_RES 1
65
66
67
68 /* Navigation grid dimensions (feet) */
69
70 #define NAV_X_MIN -22.0
71 #define NAV_X_MAX 22.0
72 #define NAV_Y_MIN -22.0
73 #define NAV_Y_MAX 22.0
74 #define NAV_Z_MIN 0.0
75 #define NAV_Z_MAX 5.0
76
77
78
79 /* Resolution of navigation grid (cells) */
80
81 #define NAV_X_RES 256
82 #define NAV_Y_RES 256
83 #define NAV_Z_RES 1
84
85
86
87 /* Sensor modes */
88
89 #define SONAR_MODE 0
90 #define LASER_MODE 1
91 #define INTEG_MODE 2
92
93 /* Sensor parameters */
94
95 /* BEGIN SCOUT THESIS CHANGE */
96
97 /* Scout and Scout2 dimensions 15.125 in sensor to sensor diameter */
98 /* Scout2 sonar height 10.25 in Scout close enough to use same value */
99 /* Height from floor to sonar (ft) Scouts 10.25 in */
100 #define SONAR_HEIGHT 0.8542
101 /* Offset from robot center to sonar (ft) Scouts 7.5625 in */
102 #define SONAR_RAD 0.63
103 /* Separation between adjacent sonars (deg) - same as Nomad 200 */
104 #define SONAR_SEP 22.5
105 /* Height from floor to IR (ft) - None on Scout */
106 #define IR_HEIGHT 0.0
107 /* Offset from robot center to IR (ft) - None on Scout */
108 #define IR_RAD 0.0
109 /* Separation between adjacent IR (deg) - None on Scout */
110 #define IR_SEP 0.0

```

```

111 /* Height from floor to laser (ft) - None on Scout */
112 #define LASER_HEIGHT 0.0
113 /* END SCOUT THESIS CHANGE */
114
115 #define HEIGHT_OFFSET 0.0 /* z-axis offset (ft) */
116
117 /* Maximum sonar reading (indicates no reflection) */
118 #define MAX_SONAR_READING 255
119
120 /* Maximum (valid) sonar range (feet) -- Use 21.25 for no truncation */
121
122 /* BEGIN SCOUT THESIS CHANGE */
123
124 /* This is the trustworthy range of the sonar in ft */
125 /* shorter range for Scout to reduce specular reflection problem */
126 #define MAX_SONAR_RANGE 8.0
127
128 /*#define MAX_SONAR_RANGE 10.0*/
129 /*#define MAX_SONAR_RANGE 21.25*/
130
131 /* Maximum sonar range for occupied cells (feet) */
132
133 /* This value seems to have no effect */
134 /*#define MAX_SONAR_OCC_RANGE 3.0*/
135 #define MAX_SONAR_OCC_RANGE 15.0
136
137 /* Maximum IR reading (indicates no reflection) */
138
139 #define MAX_IR_READING 0 /* No IR on Scout */
140
141 /* Maximum (valid) laser range (feet) */
142
143 /*#define MAX_LASER_RANGE 100.0*/
144 #define MAX_LASER_RANGE 0.0 /* No laser on Scout */
145
146 /* END SCOUT THESIS CHANGE */
147
148 /* Size of cell in robot window */
149
150 #define DISPLAY_SCALE 56.25
151
152 /* Angle conversion constants */
153
154 #define M_RAD2DEG 57.29578
155 #define M_DEG2RAD 0.017453293
156
157 /* Laser configuration parameters */
158
159 #define LASER_MODE_OFF 0x32 /* 1 100 1 1 */ /* X,Y pairs */
160 #define LASER_MODE_ON 0x33 /* 1 100 1 1 */ /* X,Y pairs */
161 #define LINE 0x03 /* 0 000 1 1 */ /* X,Y pairs for endpoints */
162 /*
163 #define THRESHHOLD 70 /* f4=30, f2.8=5, factory=20 */
164 #define WIDTH 40 /* f4=20, f2.8=20, factory=20 */
165 #define NUMDATA 120 /* Number of points returned */
166 #define AVG 1 /* Number of pixels averaged */
167
168 /* Stepsize for printing grid */

```

```

169
170 #define PRINT_STEP 1
171
172
173 /* Robot size */
174
175 /* BEGIN SCOUT THESIS CHANGE */
176 /* Scout2 is taller use its value - 14 in */
177 /* Add bumper space for total radius */
178
179 /* Robot radius (feet) Scout sensor radius plus .756 in for bumpers*/
180 #define ROBOT_RADIUS 0.693
181
182 /* Robot height (feet) use Scout2 14 in */
183 #define ROBOT_HEIGHT 1.1667
184
185 /* Size necessary for safe robot passage (feet) */
186 #define ROBOT_PASSAGE_RADIUS 0.7 /* Add small safety margin */
187
188 /* END SCOUT THESIS CHANGE */
189
190
191 /* Grid decay factor */
192
193 #define GRID_DECAY 8
194
195 /* Grid translation parameters */
196
197 #define NUM_TRANS 1 /* Number of translations in each
198 direction
199 along each axis */
200 #define TRANS_STEP 0.2 /* Size of each translation step (feet) */
201
202 /* Grid rotation parameters */
203
204 #define NUM_ROT 1 /* Number of rotations (in each direction) */
205 #define ROT_STEP 2.0 /* Rotation step (degrees) */
206
207 /* Mimimum change in position (1/10 inch) to update */
208
209 #define MIN_DELTA 46.88
210
211 /* Relative weight of clear cells in fine grid to coarse grid conversion
212 */
213
214 #define F2C_CLEAR_WT 1
215
216 /* Relative weight of occupied cells in fine grid to coarse grid
217 conversion */
218
219 #define F2C_OCC_WT 4
220
221 /* Maximum laser/sonar angle difference for laser-limited sonar
222 (degrees) */
223
224 #define LLS_MAX_ANGLE_DIFF 3.0

```

APPENDIX D. FRONTIER-BASED EXPLORATION CODE – GRID.C

This appendix contains the source code for the routine that builds the evidence grid based on the sensor return data.

```
1  /*
2
3  grid.c
4
5  Robot/evidence grid functions
6  original code by Brian Yamauchi
7
8  Modification for SCOUT THESIS
9  by Patrick A. Hillmeyer
10
11 */
12
13 #include <stdio.h>
14 #include <math.h>
15 #include "Nclient.h"
16 #include "grid.h"
17
18 double min3(double x, double y, double z)
19 /*
20  Return the minimum of three values
21 */
22 {
23     double m;      /* Minimum */
24
25     m = x;
26     if (y < m) {
27         m = y;
28     }
29     if (z < m) {
30         m = z;
31     }
32     return(m);
33 }
34
35 int world2grid(Map3D map, double wx, double wy, double wz,
36               int *gx, int *gy, int *gz)
37 /*
38  Return grid coordinates for location in world coordinates
39 */
40 {
41     double xsize, ysize, zsize;      /* Size of grid cell */
42
43     if ((wx < map.lomv[0]) || (wx > map.himv[0]) ||
44         (wy < map.lomv[1]) || (wy > map.himv[1]) ||
45         (wz < map.lomv[2]) || (wz > map.himv[2])) {
46         /* printf("world2grid: point (%f, %f, %f) out of range <%f:%f, %f:%f,
47         %f:%f>.\n",
48             wx, wy, wz, map.lomv[0], map.himv[0], map.lomv[1],
49             map.himv[1],
50             map.lomv[2], map.himv[2]); */
51         return(-1);
52     }
53 }
```

```

53
54     xsize = (map.himv[ 0] - map.lomv[ 0] ) / map.msize[ 0] ;
55     ysize = (map.himv[ 1] - map.lomv[ 1] ) / map.msize[ 1] ;
56     zsize = (map.himv[ 2] - map.lomv[ 2] ) / map.msize[ 2] ;
57
58     *gx = (int) ((wx - map.lomv[ 0] ) / xsize);
59     *gy = (int) ((wy - map.lomv[ 1] ) / ysize);
60     *gz = (int) ((wz - map.lomv[ 2] + HEIGHT_OFFSET) / zsize);
61
62     if ((*gx < 0) || (*gx >= map.msize[ 0] ) ||
63         (*gy < 0) || (*gy >= map.msize[ 1] ) ||
64         (*gz < 0) || (*gz >= map.msize[ 2] )) {
65     /*     printf("world2grid: world location (%f, %f, %f) --> cell [%d, %d,
66 %d] out of range.\n", wx, wy, wz, *gx, *gy, *gz);*/
67         return(-1);
68     }
69
70     return(1);
71 }
72
73 int world2index(Map3D map, double wx, double wy, double wz)
74 /*
75     Return grid cell index for location in world coordinates
76 */
77 {
78     double xsize, ysize, zsize;          /* Size of grid cell */
79     int gx, gy, gz;                      /* Coordinates of grid cell */
80     int index;                           /* Grid cell array index */
81
82     if ((wx < map.lomv[ 0] ) || (wx > map.himv[ 0] ) ||
83         (wy < map.lomv[ 1] ) || (wy > map.himv[ 1] ) ||
84         (wz < map.lomv[ 2] ) || (wz > map.himv[ 2] )) {
85     /*     printf("world2index (%f, %f, %f) out of range <%f:%f, %f:%f,
86 %f:%f>.\n",
87         wx, wy, wz, map.lomv[ 0] , map.himv[ 0] , map.lomv[ 1] ,
88         map.himv[ 1] ,
89         map.lomv[ 2] , map.himv[ 2] );*/
90     return(-1);
91 }
92
93     xsize = (map.himv[ 0] - map.lomv[ 0] ) / map.msize[ 0] ;
94     ysize = (map.himv[ 1] - map.lomv[ 1] ) / map.msize[ 1] ;
95     zsize = (map.himv[ 2] - map.lomv[ 2] ) / map.msize[ 2] ;
96
97     gx = (int) ((wx - map.lomv[ 0] ) / xsize);
98     gy = (int) ((wy - map.lomv[ 1] ) / ysize);
99     gz = (int) ((wz - map.lomv[ 2] + HEIGHT_OFFSET) / zsize);
100
101     index = gz * map.msize[ 0] * map.msize[ 1] + gy * map.msize[ 0] + gx;
102
103     if ((index < 0) || (index >= map.msize[ 0] * map.msize[ 1] *
104 map.msize[ 2] )) {
105     /*     printf("world2index: world location (%f, %f, %f) --> index [%d]
106 out of range.\n", wx, wy, wz, index);*/
107     return(-1);
108 }
109
110 /*     printf("world2grid: world location (%f, %f, %f) --> cell [%d, %d,
111 %d] <%d>.\n", wx, wy, wz, gx, gy, gz, index);*/

```



```

111     fflush(stdout);
112
113     return(index);
114 }
115
116 void grid2world(Map3D map, int gx, int gy, int gz,
117                double *wx, double *wy, double *wz)
118 /*
119  Return world coordinates for location in grid coordinates
120 */
121 {
122     double xsize, ysize, zsize;          /* Size of grid cell */
123     /* int tx, ty, tz; */
124
125     xsize = (map.himv[ 0] - map.lomv[ 0]) / map.msize[ 0];
126     ysize = (map.himv[ 1] - map.lomv[ 1]) / map.msize[ 1];
127     zsize = (map.himv[ 2] - map.lomv[ 2]) / map.msize[ 2];
128
129     *wx = (double) (gx + 0.5) * xsize + map.lomv[ 0];
130     *wy = (double) (gy + 0.5) * ysize + map.lomv[ 1];
131     *wz = (double) (gz + 0.5) * zsize + map.lomv[ 2];
132
133     /* if (world2grid(map, *wx, *wy, *wz, &tx, &ty, &tz) == -1) {
134         printf("<%d, %d, %d> --> (%f, %f, %f) --> <???, ???, ???>\n",
135             gx, gy, gz, *wx, *wy, *wz);
136     }
137     else {
138         printf("<%d, %d, %d> --> (%f, %f, %f) --> <%d, %d, %d>\n",
139             gx, gy, gz, *wx, *wy, *wz, tx, ty, tz);
140     } */
141 }
142
143 int grid2index(Map3D map, int gx, int gy, int gz)
144 /*
145  Return grid cell index for grid cell coordinates
146 */
147 {
148     int index;          /* Grid cell array index */
149
150     index = gz * map.msize[ 0] * map.msize[ 1] + gy * map.msize[ 0] + gx;
151     return(index);
152 }
153
154 void set_location(Map3D map, double x, double y, double z, int value)
155 /*
156  Set probability of grid cell corresponding to world location
157 */
158 {
159     int gindex;          /* Grid array index */
160
161     gindex = world2index(map, x, y, z);
162     if (gindex > -1) {
163         map.mapm[ gindex] = value;
164     }
165 }
166
167 void set_grid(Map3D map, int x, int y, int z, int value)
168 /*

```

```

169     Set probability of specified grid cell
170 */
171 {
172     int gindex;                /* Grid array index */
173
174     gindex = z * map.msize[ 0 ] * map.msize[ 1 ] + y * map.msize[ 0 ] + x;
175     if ((gindex < 0) || (gindex >= map.msize[ 0 ] * map.msize[ 1 ] *
176 map.msize[ 2 ])) {
177     /*     printf("set_grid: cell [ %d, %d, %d] out of range <%d, %d, %d>.\n",
178             x, y, z, map.msize[ 0 ], map.msize[ 1 ], map.msize[ 2 ]);*/
179         return;
180     }
181     map.mapm[ gindex ] = value;
182 }
183
184 void grid_init(Map3D *map1,    /* Grid pointer */
185               double cx, /* Center x-coord (feet) */
186               double cy) /* Center y-coord (feet) */
187 /*
188  Initialize evidence grid
189 */
190 {
191     double lov[ 3 ], hiv[ 3 ];    /* Grid corners (feet) */
192     int msize[ 3 ];              /* Grid size (cells) */
193
194     map1->cx = cx;
195     map1->cy = cy;
196
197     msize[ 0 ] = X_RES;
198     lov[ 0 ] = cx + X_MIN;
199     hiv[ 0 ] = cx + X_MAX;
200
201     msize[ 1 ] = Y_RES;
202     lov[ 1 ] = cy + Y_MIN;
203     hiv[ 1 ] = cy + Y_MAX;
204
205     msize[ 2 ] = Z_RES;
206     lov[ 2 ] = Z_MIN;
207     hiv[ 2 ] = Z_MAX;
208
209     MakeMap3D(msize, lov, hiv, map1);
210 }
211
212 void grid_init_global(Map3D *map1, /* Grid pointer */
213                      double cx, /* Center x-coord (feet) */
214                      double cy) /* Center y-coord (feet) */
215 /*
216  Initialize global evidence grid
217 */
218 {
219     double lov[ 3 ], hiv[ 3 ];    /* Grid corners (feet) */
220     int msize[ 3 ];              /* Grid size (cells) */
221
222     map1->cx = cx;
223     map1->cy = cy;
224
225     msize[ 0 ] = GLOBAL_X_RES;
226     lov[ 0 ] = cx + GLOBAL_X_MIN;

```

```

227     hiv[ 0] = cx + GLOBAL_X_MAX;
228
229     msize[ 1] = GLOBAL_Y_RES;
230     lov[ 1] = cy + GLOBAL_Y_MIN;
231     hiv[ 1] = cy + GLOBAL_Y_MAX;
232
233     msize[ 2] = GLOBAL_Z_RES;
234     lov[ 2] = GLOBAL_Z_MIN;
235     hiv[ 2] = GLOBAL_Z_MAX;
236
237     MakeMap3D(msize, lov, hiv, map1);
238 }
239
240 void grid_init_nav(Map3D *map1,      /* Grid pointer */
241                   double cx,        /* Center x-coord (feet) */
242                   double cy)        /* Center y-coord (feet) */
243 /*
244  Initialize evidence grid for navigation
245 */
246 {
247     double lov[ 3], hiv[ 3];        /* Grid corners (feet) */
248     int msize[ 3];                  /* Grid size (cells) */
249
250     map1->cx = cx;
251     map1->cy = cy;
252
253     msize[ 0] = NAV_X_RES;
254     lov[ 0] = cx + NAV_X_MIN;
255     hiv[ 0] = cx + NAV_X_MAX;
256
257     msize[ 1] = NAV_Y_RES;
258     lov[ 1] = cy + NAV_Y_MIN;
259     hiv[ 1] = cy + NAV_Y_MAX;
260
261     msize[ 2] = NAV_Z_RES;
262     lov[ 2] = NAV_Z_MIN;
263     hiv[ 2] = NAV_Z_MAX;
264
265     MakeMap3D(msize, lov, hiv, map1);
266 }
267
268 void grid_print(Map3D map, int yaxis)
269 /*
270  Print evidence grid occupancy probabilities
271 */
272 {
273     int x, y, z;                    /* Cell index */
274     int xsize, ysize, zsize;        /* Grid dimensions (# cells) */
275     int p;                          /* Occupancy probability */
276     int empty;                      /* Empty level flag */
277
278     xsize = map.msize[ 0];
279     ysize = map.msize[ 1];
280     zsize = map.msize[ 2];
281
282     for (z = 0; z < zsize; z++) {
283         y = x = 0;
284         empty = 1;

```

```

285 while((y < ysize) && (x < xsize) && empty) {
286     if (map.mapm[ z * xsize * ysize + y * xsize + x] != 0) {
287         empty = 0;
288     }
289     x++;
290     if (x == xsize) {
291         x = 0;
292         y++;
293     }
294 }
295
296 if (!empty) {
297     printf("Level: %d\n\n", z);
298
299     for (y = 0; y < ysize; y++) {
300         for (x = 0; x < xsize; x++) {
301             if (yaxis == 1) {
302                 p = map.mapm[ z * xsize * ysize + (ysize - y - 1) * xsize + x];
303             }
304             else {
305                 p = map.mapm[ z * xsize * ysize + y * xsize + x];
306             }
307             if (p > 0) {
308                 printf("#");
309             }
310             else if (p == 0) {
311                 printf("?");
312             }
313             else if (p > -25) {
314                 printf(":");
315             }
316             else if (p > -50) {
317                 printf(".");
318             }
319             else {
320                 printf(" ");
321             }
322         }
323         printf("\n");
324     }
325     getchar();
326 }
327 }
328 }
329
330 void sonar_print(Map3D map, int yaxis)
331 /*
332  Print evidence grid occupancy probabilities for sonar level
333 */
334 {
335     int x, y, z; /* Cell index */
336     int xsize, ysize, zsize; /* Grid dimensions (# cells) */
337     int p; /* Occupancy probability */
338     int empty; /* Empty level flag */
339
340     xsize = map.msize[ 0];
341     ysize = map.msize[ 1];
342     zsize = map.msize[ 2];

```

```

343
344 z = (int) ((SONAR_HEIGHT + HEIGHT_OFFSET - map.lomv[ 2] ) /
345             (map.himv[ 2] - map.lomv[ 2] ) * zsize);
346
347 printf("");
348 for (y = 0; y < ysize; y += PRINT_STEP) {
349     for (x = 0; x < xsize; x += PRINT_STEP) {
350         if (yaxis == 1) {
351             p = map.mapm[ z * xsize * ysize + (ysize - y - 1) * xsize + x];
352         }
353         else {
354             p = map.mapm[ z * xsize * ysize + y * xsize + x];
355         }
356         if (p > 0) {
357             printf("#");
358         }
359         else if (p == 0) {
360             printf("?");
361         }
362         else if (p > -25) {
363             printf(":");
364         }
365         else if (p > -50) {
366             printf(".");
367         }
368         else {
369             printf(" ");
370         }
371     }
372     printf("\n");
373 }
374 }
375
376 void laser_print(Map3D map, int yaxis)
377 /*
378  Print evidence grid occupancy probabilities for sonar level
379 */
380 {
381     int x, y, z;                /* Cell index */
382     int xsize, ysize, zsize;    /* Grid dimensions (# cells) */
383     int p;                      /* Occupancy probability */
384     int empty;                  /* Empty level flag */
385
386     xsize = map.msize[ 0];
387     ysize = map.msize[ 1];
388     zsize = map.msize[ 2];
389
390     z = (int) ((LASER_HEIGHT + HEIGHT_OFFSET - map.lomv[ 2] ) /
391               (map.himv[ 2] - map.lomv[ 2] ) * zsize);
392
393     printf("");
394     for (y = 0; y < ysize; y += PRINT_STEP) {
395         for (x = 0; x < xsize; x += PRINT_STEP) {
396             if (yaxis == 1) {
397                 p = map.mapm[ z * xsize * ysize + (ysize - y - 1) * xsize + x];
398             }
399             else {
400                 p = map.mapm[ z * xsize * ysize + y * xsize + x];

```



```

401     }
402     if (p > 0) {
403         printf("#");
404     }
405     else if (p == 0) {
406         printf("?");
407     }
408     else if (p > -25) {
409         printf(":");
410     }
411     else if (p > -50) {
412         printf(".");
413     }
414     else {
415         printf(" ");
416     }
417 }
418 printf("\n");
419 }
420 }
421
422 void grid_display(Map3D map,          /* Evidence grid */
423                  double height,      /* z-coord of plane to display */
424                  int x_origin,       /* World x-coord of origin (1/10 inch)*/
425                  int y_origin)      /* World y-coord of origin (1/10 inch)*/
426 /*
427  Display evidence grid occupancy probabilities in robot window
428 */
429 {
430     double xd, yd;                  /* Display coords */
431     double xscale, yscale, zscale; /* Cell dimensions (tenths of
432 inches) */
433     double xoffset, yoffset;        /* Circle center offset */
434     int x, y, z;                   /* Cell index */
435     int xsize, ysize, zsize;        /* Grid dimensions (# cells) */
436     int p;                         /* Occupancy probability */
437     int empty;                     /* Empty level flag */
438     /* int rad;*/                  /* Radius of cell display */
439
440     printf("Displaying grid at (%d, %d)\n", x_origin, y_origin);
441
442     xsize = map.msize[ 0 ];
443     ysize = map.msize[ 1 ];
444     zsize = map.msize[ 2 ];
445
446     xscale = (map.himv[ 0 ] - map.lomv[ 0 ]) * 120.0 / (double) xsize;
447     yscale = (map.himv[ 1 ] - map.lomv[ 1 ]) * 120.0 / (double) ysize;
448     zscale = (map.himv[ 2 ] - map.lomv[ 2 ]) * 120.0 / (double) zsize;
449
450     xoffset = xscale / 2.0;
451     yoffset = yscale / 2.0;
452
453     z = (int) ((height + HEIGHT_OFFSET - map.lomv[ 2 ]) /
454               (map.himv[ 2 ] - map.lomv[ 2 ]) * zsize);
455
456     for (y = 0; y < ysize; y++) {
457         for (x = 0; x < xsize; x++) {
458             p = map.mapm[ z * xsize * ysize + y * xsize + x ];

```

```

459
460     xd = (int) ((double) x * xscale + map.lomv[0] * 120.0) + x_origin;
461     yd = (int) ((double) y * yscale + map.lomv[1] * 120.0) + y_origin;
462
463     /*     rad = (int) (((double) (p - NEG) / (double) POS) * (double)
464     xscale * 0.5);
465
466     draw_arc(xd, yd, rad, rad, 0, 3600, 1);*/
467
468     if (p > 0) {
469         draw_arc(xd, yd, xscale, yscale, 0, 3600, 1);
470     }
471     else if (p == 0) {
472         draw_arc(xd, yd, xscale / 4.0, xscale / 4.0, 0, 3600, 1);
473     }
474 }
475 }
476 }
477
478 void grid_display_pos(Map3D map,          /* Evidence grid */
479                      double height)      /* z-coord of plane to display */
480 /*
481  Display evidence grid occupancy probabilities in robot window at
482  position
483  */
484 {
485     int dx, dy;
486
487     printf("Enter display coordinates ==> ");
488     scanf(" %d %d", &dx, &dy);
489
490     grid_display(map, height, dx, dy);
491 }
492
493 void model_init(CylSensorModelArray *sonar_smd,
494                CylSensorModelArray *sonar_clear_smd)
495 /*
496  Initialize sensor models
497  */
498 {
499     InitCylModelParams();
500
501     MakeCylModel(66, 0.02, 64, 128, 1.0, 22.0, sonar_smd);
502     TrimCylModel(*sonar_smd);
503
504     /* WriteCylModel(*sonar_smd, "sonar.mod");*/
505     /* ReadCylModel("sonar.mod", sonar_smd);*/
506
507     MakeClearCylModel(66, 0.02, 64, 128, 1.0, 22.0, sonar_clear_smd);
508     TrimCylModel(*sonar_clear_smd);
509
510     /* WriteCylModel(*sonar_clear_smd, "clear.mod");*/
511     /* ReadCylModel("clear.mod", sonar_clear_smd);*/
512 }
513
514 void sonar_scan(CylSensorModelArray smd, CylSensorModelArray clear_smd,
515                Map3D map, int rx, int ry, int rtheta)
516 /*

```

```

517     Update evidence grid using all sonar sensors
518 */
519 {
520     PosData sonar_pose[ 16 ];      /* Sonar pose information */
521     double robot_x, robot_y;      /* Robot position */
522     double robot_theta;          /* Robot heading */
523     double range;                /* Range reading (feet) */
524     double angle;                /* Sensor angle (radians) */
525     double sonar_pos[ 3 ];        /* Sonar position */
526     double sonar_dir[ 3 ];        /* Sonar direction */
527     int reading;                 /* Raw sonar reading */
528     int i;                       /* Sonar index */
529
530     gs(); /* SCOUT THESIS CHANGE use gs to get sonar and position info */
531
532     /* posSonarRingGet(sonar_pose); SCOUT THESIS CHANGE - comment this
533     line out */
534     /* SCOUT does not currently provide pose data as NOMAD 200 does */
535
536     for (i = 0; i < 16; i++) {
537         /* SCOUT THESIS CHANGE
538         comment out the requests for pose information below
539         robot_x = (double) sonar_pose[i].config.configX / 120.0; commented out
540         robot_y = (double) sonar_pose[i].config.configY / 120.0; commented out
541         robot_theta = (double) sonar_pose[i].config.configTurret / 10.0;
542         commented out
543         */
544
545         /* SCOUT THESIS CHANGE uncomment out the lines below
546         and get the sonar data from using the gs command */
547         robot_x = (double) rx / 120.0;
548         robot_y = (double) ry / 120.0;
549         robot_theta = (double) rtheta / 10.0;
550
551         reading = State[ i + 17 ];
552         range = (double) reading / 12.0;
553         angle = ((double) i * SONAR_SEP + robot_theta) * M_DEG2RAD;
554
555         sonar_dir[ 0 ] = cos(angle);
556         sonar_dir[ 1 ] = sin(angle);
557         sonar_dir[ 2 ] = 0.0;
558
559         sonar_pos[ 0 ] = sonar_dir[ 0 ] * SONAR_RAD;
560         sonar_pos[ 1 ] = sonar_dir[ 1 ] * SONAR_RAD;
561         sonar_pos[ 2 ] = SONAR_HEIGHT + HEIGHT_OFFSET;
562
563         if ((reading != MAX_SONAR_READING) && (range <= MAX_SONAR_RANGE)){
564             AddCylReading(range, sonar_pos, sonar_dir, smd, map);
565         }
566         else {
567             AddCylReading(MAX_SONAR_RANGE, sonar_pos, sonar_dir, clear_smd,
568             map);
569         }
570     }
571 }
572
573 void sonar_scan_abs(CylSensorModelArray smd, CylSensorModelArray
574 clear_smd,

```

```

575         Map3D map, int rx, int ry, int rtheta)
576     /*
577     Update evidence grid using all sonar sensors (using absolute position)
578     */
579     {
580         PosData sonar_pose[16];      /* Sonar pose information */
581         double robot_x, robot_y;     /* Robot position */
582         double robot_theta;          /* Robot heading */
583         double range;                /* Range reading (feet) */
584         double angle;                /* Sensor angle (radians) */
585         double sonar_pos[3];         /* Sonar position */
586         double sonar_dir[3];         /* Sonar direction */
587         int reading;                  /* Raw sonar reading */
588         int i;                        /* Sonar index */
589
590         gs();
591         /* posSonarRingGet(sonar_pose); SCOUT THESIS CHANGE - comment this
592         line out */
593         /* SCOUT does not currently provide for pose data as the NOMAD 200 does
594         */
595
596         for (i = 0; i < 16; i++) {
597             /* robot_x = (double) sonar_pose[i].config.configX / 120.0; **
598             comment this line out */
599             /* robot_y = (double) sonar_pose[i].config.configY / 120.0; **
600             comment out */
601             /* robot_theta = (double) sonar_pose[i].config.configTurret / 10.0;
602             ** comment out */
603
604             /* uncomment out the lines below and use gs command to get sonar data
605             */
606             robot_x = (double) rx / 120.0;
607             robot_y = (double) ry / 120.0;
608             robot_theta = (double) rtheta / 10.0;
609
610             reading = State[i + 17];
611             range = (double) reading / 12.0;
612             angle = ((double) i * SONAR_SEP + robot_theta) * M_DEG2RAD;
613
614             sonar_dir[0] = cos(angle);
615             sonar_dir[1] = sin(angle);
616             sonar_dir[2] = 0.0;
617
618             sonar_pos[0] = sonar_dir[0] * SONAR_RAD + robot_x;
619             sonar_pos[1] = sonar_dir[1] * SONAR_RAD + robot_y;
620             sonar_pos[2] = SONAR_HEIGHT + HEIGHT_OFFSET;
621
622             if ((reading != MAX_SONAR_READING) && (range <= MAX_SONAR_RANGE)){
623                 AddCylReading(range, sonar_pos, sonar_dir, smd, map);
624             }
625             else {
626                 AddCylReading(MAX_SONAR_RANGE, sonar_pos, sonar_dir, clear_smd,
627                 map);
628             }
629         }
630     }
631 }
632

```

```

633
634 /* BEGIN SCOUT CHANGE */
635 /* NOTE - it appears that the following function is never used by any
636 exploration routine */
637 /* Left in code for now since it will not affect the Scout */
638 /* The header for this is in grid++.h */
639
640 void ir_scan_abs(CylSensorModelArray smd, CylSensorModelArray clear_smd,
641                 Map3D map, int rx, int ry, int rtheta)
642 /*
643  Update evidence grid using all infrared sensors (using absolute
644 position)
645 */
646 {
647     PosData ir_pose[ 16];          /* IR pose information */
648     double robot_x, robot_y;       /* Robot position */
649     double robot_theta;            /* Robot heading */
650     double range;                  /* Range reading (feet) */
651     double angle;                  /* Sensor angle (radians) */
652     double ir_pos[ 3];             /* IR position */
653     double ir_dir[ 3];             /* IR direction */
654     int reading;                   /* Raw IR reading */
655     int i;                         /* Sonar index */
656
657     gs();
658     posInfraredRingGet(ir_pose);
659
660     for (i = 0; i < 16; i++) {
661         robot_x = (double) ir_pose[i].config.configX / 120.0;
662         robot_y = (double) ir_pose[i].config.configY / 120.0;
663         robot_theta = (double) ir_pose[i].config.configTurret / 10.0;
664
665         /* robot_x = (double) rx / 120.0;
666         robot_y = (double) ry / 120.0;
667         robot_theta = (double) rtheta / 120.0;*/
668
669         reading = State[i + 17];
670         range = (double) reading / 12.0;
671         angle = ((double) i * IR_SEP + robot_theta) * M_DEG2RAD;
672
673         ir_dir[ 0] = cos(angle);
674         ir_dir[ 1] = sin(angle);
675         ir_dir[ 2] = 0.0;
676
677         ir_pos[ 0] = ir_dir[ 0] * IR_RAD + robot_x;
678         ir_pos[ 1] = ir_dir[ 1] * IR_RAD + robot_y;
679         ir_pos[ 2] = IR_HEIGHT + HEIGHT_OFFSET;
680
681         if (reading < MAX_IR_READING) {
682             AddCylReading(range, ir_pos, ir_dir, smd, map);
683         }
684     }
685 }
686
687 /* END SCOUT CHANGE */
688
689
690 void sonar_scan_abs_norep(CylSensorModelArray smd,

```



```

691         CylSensorModelArray clear_smd,
692         Map3D map, int rx, int ry, int rtheta)
693     /*
694     Update evidence grid using all sonar sensors (using absolute position)
695     (no updates for repeated positions)
696     */
697     {
698         static long old_x[16], old_y[16]; /* Old robot position */
699         static int first_flag = 1; /* Reset first time function is called */
700
701         PosData sonar_pose[16]; /* Sonar pose information */
702         double robot_x, robot_y; /* Robot position */
703         double delta; /* Change in robot position since last
704         update */
705         double robot_theta; /* Robot heading */
706         double range; /* Range reading (feet) */
707         double angle; /* Sensor angle (radians) */
708         double sonar_pos[3]; /* Sonar position */
709         double sonar_dir[3]; /* Sonar direction */
710         int reading; /* Raw sonar reading */
711         int i; /* Sonar index */
712
713         gs();
714         posSonarRingGet(sonar_pose);
715
716         for (i = 0; i < 16; i++) {
717             robot_x = (double) sonar_pose[i].config.configX / 120.0;
718             robot_y = (double) sonar_pose[i].config.configY / 120.0;
719             robot_theta = (double) sonar_pose[i].config.configTurret / 10.0;
720
721             delta = hypot((double) (sonar_pose[i].config.configX - old_x[i]),
722                         (double) (sonar_pose[i].config.configY - old_y[i]));
723
724             if (first_flag || delta >= MIN_DELTA) {
725                 old_x[i] = sonar_pose[i].config.configX;
726                 old_y[i] = sonar_pose[i].config.configY;
727
728                 reading = State[i + 17];
729                 range = (double) reading / 12.0;
730                 angle = ((double) i * SONAR_SEP + robot_theta) * M_DEG2RAD;
731
732                 sonar_dir[0] = cos(angle);
733                 sonar_dir[1] = sin(angle);
734                 sonar_dir[2] = 0.0;
735
736                 sonar_pos[0] = sonar_dir[0] * SONAR_RAD + robot_x;
737                 sonar_pos[1] = sonar_dir[1] * SONAR_RAD + robot_y;
738                 sonar_pos[2] = SONAR_HEIGHT + HEIGHT_OFFSET;
739
740                 if ((reading != MAX_SONAR_READING) && (range <= MAX_SONAR_RANGE)){
741                     AddCylReading(range, sonar_pos, sonar_dir, smd, map);
742                 }
743                 else {
744                     AddCylReading(MAX_SONAR_RANGE, sonar_pos, sonar_dir, clear_smd,
745                     map);
746                 }
747             }
748             /* else {

```

```

749         printf("sonar_scan_abs_norep: Repeated position (%d, %d) for
750 sensor %d.\n",
751         old_x[i], old_y[i], i);
752     } */
753 }
754
755     first_flag = 0;
756 }
757
758 void laser_update(Map3D map, double rx, double ry, double lx, double ly,
759                 double rtheta)
760 /*
761  * Update evidence grid for a single laser reading
762  */
763 {
764     double lr, ltheta;           /* Laser vector */
765     double wx, wy;               /* World coords of laser endpoint */
766     double xsize, ysize;         /* Size of grid cell */
767     double stepsize;             /* Stepsize along laser axis */
768     double dx, dy;               /* Stepsize along x and y axes */
769     double px, py;               /* Point currently being updated */
770     int steps;                   /* Number of steps */
771     int i;
772
773     lr = hypot(lx, ly);
774     ltheta = atan2(ly, lx) * M_RAD2DEG;
775
776     wx = rx + lr * cos((ltheta + rtheta) * M_DEG2RAD);
777     wy = ry + lr * sin((ltheta + rtheta) * M_DEG2RAD);
778
779     set_location(map, wx, wy, LASER_HEIGHT, POS);
780
781     px = rx;
782     py = ry;
783
784     xsize = (map.himv[0] - map.lomv[0]) / map.msize[0];
785     ysize = (map.himv[1] - map.lomv[1]) / map.msize[1];
786
787     if (xsize < ysize) {
788         stepsize = xsize;
789     }
790     else {
791         stepsize = ysize;
792     }
793
794     dx = stepsize * cos((ltheta + rtheta) * M_DEG2RAD);
795     dy = stepsize * sin((ltheta + rtheta) * M_DEG2RAD);
796
797     steps = (int) (lr / stepsize);
798
799     for (i = 0; i < steps; i++) {
800         set_location(map, px, py, LASER_HEIGHT, NEG);
801         px += dx;
802         py += dy;
803     }
804 }
805
806 void laser_scan(Map3D map, int rx, int ry, int rtheta)

```

```

807  /*
808  Update evidence grid using laser scanner
809  */
810  {
811      PosData laser_pose;          /* Laser pose information */
812      double lx, ly, lr, ltheta;   /* Laser point (robot coordinates) */
813      double wx, wy, wz;          /* Laser point (world coordinates) */
814      double robot_x, robot_y, robot_theta; /* Robot location */
815      int i;
816
817      gs();
818      posLaserGet(&laser_pose);
819
820      robot_x = (double) laser_pose.config.configX / 120.0;
821      robot_y = (double) laser_pose.config.configY / 120.0;
822      robot_theta = (double) laser_pose.config.configTurret / 10.0;
823
824      for (i = 0; i < Laser[0]; i++) {
825          /*      printf("[%d, %d] ", Laser[i * 2 + 1], Laser[i * 2 + 2]); */
826          if (Laser[i * 2 + 1] != 65000) {
827              lx = (double) Laser[i * 2 + 1] / 120.0;
828              ly = (double) Laser[i * 2 + 2] / 120.0;
829              /*      printf("(%f, %f)", lx, ly); */
830
831              /*      laser_update(map, robot_x, robot_y, lx, ly, robot_theta); */
832
833              lr = hypot(lx, ly);
834              ltheta = atan2(ly, lx) * M_RAD2DEG;
835
836              if (lr <= MAX_LASER_RANGE) {
837                  wx = lr * cos((ltheta + robot_theta) * M_DEG2RAD);
838                  wy = lr * sin((ltheta + robot_theta) * M_DEG2RAD);
839                  wz = LASER_HEIGHT + HEIGHT_OFFSET;
840                  set_location(map, wx, wy, wz, POS);
841                  /*      draw_line((int) robot_x * 120.0, (int) robot_y *
842 120.0, (int) wx * 120.0,
843 (int) wy * 120.0, 19); */
844              }
845          }
846          /*      printf("\n"); */
847      }
848  }
849
850  void laser_scan_abs(Map3D map, int rx, int ry, int rtheta)
851  /*
852  Update evidence grid using laser scanner (using absolute position)
853  */
854  {
855      PosData laser_pose;          /* Laser pose information */
856      double lx, ly, lr, ltheta;   /* Laser point (robot coordinates) */
857      double wx, wy, wz;          /* Laser point (world coordinates) */
858      double robot_x, robot_y, robot_theta; /* Robot location */
859      int i;
860
861      gs();
862      posLaserGet(&laser_pose);
863
864      robot_x = (double) laser_pose.config.configX / 120.0;

```

```

865 robot_y = (double) laser_pose.config.configY / 120.0;
866 robot_theta = (double) laser_pose.config.configTurret / 10.0;
867
868 for (i = 0; i < Laser[ 0]; i++) {
869     /*      printf("[%d, %d] ", Laser[ i * 2 + 1], Laser[ i * 2 + 2]);*/
870     if (Laser[ i * 2 + 1] != 65000) {
871         lx = (double) Laser[ i * 2 + 1] / 120.0;
872         ly = (double) Laser[ i * 2 + 2] / 120.0;
873         /*      printf("(%.f, %.f)", lx, ly);*/
874
875     /*      laser_update(map, robot_x, robot_y, lx, ly, robot_theta);*/
876
877     lr = hypot(lx, ly);
878     ltheta = atan2(ly, lx) * M_RAD2DEG;
879
880     if (lr <= MAX_LASER_RANGE) {
881         wx = lr * cos((ltheta + robot_theta) * M_DEG2RAD) + robot_x;
882         wy = lr * sin((ltheta + robot_theta) * M_DEG2RAD) + robot_y;
883         wz = LASER_HEIGHT + HEIGHT_OFFSET;
884         set_location(map, wx, wy, wz, POS);
885         /*      draw_line((int) robot_x * 120.0, (int) robot_y *
886 120.0, (int) wx * 120.0,
887 (int) wy * 120.0, 19);*/
888     }
889 }
890 /*      printf("\n");*/
891 }
892 }
893
894 double laser_min(void)
895 /*
896 Return minimum laser range reading
897 */
898 {
899     double min_range = MAX_LASER_RANGE;    /* Minimum range reading */
900     double lx, ly, lr, ltheta;            /* Laser point (robot coordinates)
901 */
902     int i;
903
904     gs();
905
906     for (i = 0; i < Laser[ 0]; i++) {
907         if (Laser[ i * 2 + 1] != 65000) {
908             lx = (double) Laser[ i * 2 + 1] / 120.0;
909             ly = (double) Laser[ i * 2 + 2] / 120.0;
910
911             lr = hypot(lx, ly);
912
913             if (lr < min_range) {
914                 min_range = lr;
915             }
916         }
917     }
918
919     return(min_range);
920 }
921
922 void lls_scan(CylSensorModelArray smd, CylSensorModelArray clear_smd,

```

```

923         Map3D map, int rx, int ry, int rtheta)
924     /*
925     Update evidence grid using laser-limited sonar
926     */
927
928     {
929         PosData sonar_pose[ 16];      /* Sonar pose information */
930         PosData ir_pose[ 16];         /* IR pose information */
931         PosData laser_pose;           /* Laser pose information */
932         double sonar_x, sonar_y;      /* Sonar position */
933         double sonar_theta;           /* Sonar angle */
934         double laser_x, laser_y;      /* Laser position */
935         double laser_theta;           /* Laser angle */
936         double lx, ly, lr, ltheta;    /* Laser point (robot coordinates) */
937         double wx, wy, wz;            /* Laser point (world coordinates) */
938         double min_laser_range = MAX_LASER_RANGE; /* Minimum laser reading
939     */
940         double sonar_range;            /* Range reading (feet) */
941         double angle;                  /* Sensor angle (radians) */
942         double sonar_pos[ 3];         /* Sonar position */
943         double sonar_dir[ 3];         /* Sonar direction */
944         double angle_diff;             /* Angle offset between laser and sonar */
945         int reading;                   /* Raw sonar reading */
946         int i;
947
948         /* Get sensor and pose data from robot */
949
950         gs();
951         posSonarRingGet(sonar_pose);
952         posInfraredRingGet(ir_pose);
953         posLaserGet(&laser_pose);
954
955         /* Update grid using laser readings */
956
957         laser_x = (double) laser_pose.config.configX / 120.0;
958         laser_y = (double) laser_pose.config.configY / 120.0;
959         laser_theta = (double) laser_pose.config.configTurret / 10.0;
960
961         for (i = 0; i < Laser[ 0]; i++) {
962             /*      printf("[ %d, %d] ", Laser[ i * 2 + 1], Laser[ i * 2 + 2]);*/
963             if (Laser[ i * 2 + 1] != 65000) {
964                 lx = (double) Laser[ i * 2 + 1] / 120.0;
965                 ly = (double) Laser[ i * 2 + 2] / 120.0;
966                 /*      printf("( %f, %f)", lx, ly);*/
967
968             /*      laser_update(map, laser_x, laser_y, lx, ly, laser_theta);*/
969
970                 lr = hypot(lx, ly);
971                 if (lr < min_laser_range) {
972                     min_laser_range = lr;
973                 }
974
975                 ltheta = atan2(ly, lx) * M_RAD2DEG;
976
977                 if (lr <= MAX_LASER_RANGE) {
978                     wx = lr * cos((ltheta + laser_theta) * M_DEG2RAD);
979                     wy = lr * sin((ltheta + laser_theta) * M_DEG2RAD);
980                     wz = LASER_HEIGHT + HEIGHT_OFFSET;

```



```

981         set_location(map, wx, wy, wz, POS);
982         /*          draw_line((int) laser_x * 120.0, (int) laser_y *
983 120.0, (int) wx * 120.0,
984         (int) wy * 120.0, 19);*/
985     }
986 }
987 /*      printf("\n");*/
988 }
989
990 /* Update grid using sonar reading (limited by minimum laser range) */
991
992 sonar_x = (double) sonar_pose[0].config.configX / 120.0;
993 sonar_y = (double) sonar_pose[0].config.configY / 120.0;
994 sonar_theta = (double) sonar_pose[0].config.configTurret / 10.0;
995
996 reading = State[17];
997
998 /* At very close ranges, use infrared instead */
999
1000 /*  if (State[1] < MAX_IR_READING) {
1001     reading = State[1];
1002
1003     sonar_x = (double) ir_pose[0].config.configX / 120.0;
1004     sonar_y = (double) ir_pose[0].config.configY / 120.0;
1005     sonar_theta = (double) ir_pose[0].config.configTurret / 10.0;
1006
1007     printf("laser/IR offset = %f inches : %f degrees\n",
1008     hypot(sonar_x - laser_x, sonar_y - laser_y),
1009     sonar_theta - laser_theta);
1010 }
1011 else {
1012     printf("laser/sonar offset = %f inches : %f degrees\n",
1013     hypot(sonar_x - laser_x, sonar_y - laser_y),
1014     sonar_theta - laser_theta);
1015 }*/
1016
1017 /* Compute angle offset between laser and sonar (or IR) */
1018
1019 angle_diff = fabs(sonar_theta - laser_theta);
1020 if (angle_diff > 180.0) {
1021     angle_diff = 360.0 - angle_diff;
1022 }
1023
1024 /* Discard reading if offset is too large */
1025
1026 if (angle_diff > LLS_MAX_ANGLE_DIFF) {
1027     printf("LLS reading discarded: angle offset = %f\n", angle_diff);
1028     return;
1029 }
1030
1031 /* Determine LLS range */
1032
1033 sonar_range = (double) reading / 12.0;
1034
1035 if (sonar_range > min_laser_range) {
1036     sonar_range = min_laser_range;
1037 }
1038

```

```

1039  /* Update grid */
1040
1041  angle = sonar_theta * M_DEG2RAD;
1042
1043  sonar_dir[ 0] = cos(angle);
1044  sonar_dir[ 1] = sin(angle);
1045  sonar_dir[ 2] = 0.0;
1046
1047  sonar_pos[ 0] = sonar_dir[ 0] * SONAR_RAD;
1048  sonar_pos[ 1] = sonar_dir[ 1] * SONAR_RAD;
1049  sonar_pos[ 2] = SONAR_HEIGHT + HEIGHT_OFFSET;
1050
1051  if ((reading != MAX_SONAR_READING) && (sonar_range <=
1052  MAX_SONAR_RANGE)){
1053      if (sonar_range <= MAX_SONAR_OCC_RANGE) {
1054          AddCylReading(sonar_range, sonar_pos, sonar_dir, smd, map);
1055      }
1056      else {
1057          AddCylReading(sonar_range, sonar_pos, sonar_dir, clear_smd, map);
1058      }
1059  }
1060  else {
1061      AddCylReading(MAX_SONAR_RANGE, sonar_pos, sonar_dir, clear_smd,
1062  map);
1063  }
1064  }
1065
1066  void lls_scan_abs(CylSensorModelArray smd, CylSensorModelArray
1067  clear_smd,
1068                  Map3D map, int rx, int ry, int rtheta)
1069  /*
1070   Update evidence grid using laser-limited sonar (absolute coordinates)
1071  */
1072  {
1073      PosData sonar_pose[ 16]; /* Sonar pose information */
1074      PosData ir_pose[ 16]; /* IR pose information */
1075      PosData laser_pose; /* Laser pose information */
1076      double sonar_x, sonar_y; /* Sonar position */
1077      double sonar_theta; /* Sonar angle */
1078      double laser_x, laser_y; /* Laser position */
1079      double laser_theta; /* Laser angle */
1080      double lx, ly, lr, ltheta; /* Laser point (robot coordinates) */
1081      double wx, wy, wz; /* Laser point (world coordinates) */
1082      double min_laser_range = MAX_LASER_RANGE; /* Minimum laser reading
1083  */
1084      double sonar_range; /* Range reading (feet) */
1085      double angle; /* Sensor angle (radians) */
1086      double sonar_pos[ 3]; /* Sonar position */
1087      double sonar_dir[ 3]; /* Sonar direction */
1088      double angle_diff; /* Angle offset between laser and sonar */
1089      int reading; /* Raw sonar reading */
1090      int i;
1091
1092
1093      /* Get sensor and pose data from robot */
1094
1095      gs();
1096      posSonarRingGet(sonar_pose);

```

```

1097 posInfraredRingGet(ir_pose);
1098 posLaserGet(&laser_pose);
1099
1100 /* Update grid using laser readings */
1101
1102 laser_x = (double) laser_pose.config.configX / 120.0;
1103 laser_y = (double) laser_pose.config.configY / 120.0;
1104 laser_theta = (double) laser_pose.config.configTurret / 10.0;
1105
1106 for (i = 0; i < Laser[0]; i++) {
1107     /* printf("[ %d, %d] ", Laser[ i * 2 + 1], Laser[ i * 2 + 2] );*/
1108     if (Laser[ i * 2 + 1] != 65000) {
1109         lx = (double) Laser[ i * 2 + 1] / 120.0;
1110         ly = (double) Laser[ i * 2 + 2] / 120.0;
1111         /* printf("( %f, %f)", lx, ly);*/
1112
1113         /* laser_update(map, laser_x, laser_y, lx, ly, laser_theta);*/
1114
1115         lr = hypot(lx, ly);
1116         if (lr < min_laser_range) {
1117             min_laser_range = lr;
1118         }
1119
1120         ltheta = atan2(ly, lx) * M_RAD2DEG;
1121
1122         if (lr <= MAX_LASER_RANGE) {
1123             wx = lr * cos((ltheta + laser_theta) * M_DEG2RAD) + laser_x;
1124             wy = lr * sin((ltheta + laser_theta) * M_DEG2RAD) + laser_y;
1125             wz = LASER_HEIGHT + HEIGHT_OFFSET;
1126             set_location(map, wx, wy, wz, POS);
1127             /* draw_line((int) laser_x * 120.0, (int) laser_y *
1128 120.0, (int) wx * 120.0,
1129 (int) wy * 120.0, 19);*/
1130         }
1131     }
1132     /* printf("\n");*/
1133 }
1134
1135 /* Update grid using sonar reading (limited by minimum laser range) */
1136
1137 sonar_x = (double) sonar_pose[0].config.configX / 120.0;
1138 sonar_y = (double) sonar_pose[0].config.configY / 120.0;
1139 sonar_theta = (double) sonar_pose[0].config.configTurret / 10.0;
1140
1141 reading = State[17];
1142
1143 /* At very close ranges, use infrared instead */
1144
1145 /* if (State[1] < MAX_IR_READING) {
1146     reading = State[1];
1147
1148     sonar_x = (double) ir_pose[0].config.configX / 120.0;
1149     sonar_y = (double) ir_pose[0].config.configY / 120.0;
1150     sonar_theta = (double) ir_pose[0].config.configTurret / 10.0;
1151
1152     printf("IR/sonar offset = %f inches : %f degrees\n",
1153 hypot(sonar_x - laser_x, sonar_y - laser_y),
1154 sonar_theta - laser_theta);

```

```

1155     }
1156     else {
1157         printf("laser/sonar offset = %f inches : %f degrees\n",
1158             hypot(sonar_x - laser_x, sonar_y - laser_y),
1159             sonar_theta - laser_theta);
1160     }*/
1161
1162     /* Compute angle offset between laser and sonar (or IR) */
1163
1164     angle_diff = fabs(sonar_theta - laser_theta);
1165     if (angle_diff > 180.0) {
1166         angle_diff = 360.0 - angle_diff;
1167     }
1168
1169     /* Discard reading if offset is too large */
1170
1171     if (angle_diff > LLS_MAX_ANGLE_DIFF) {
1172         printf("LLS reading discarded: angle offset = %f\n", angle_diff);
1173         return;
1174     }
1175
1176     /* Determine LLS range */
1177
1178     sonar_range = (double) reading / 12.0;
1179
1180     if (sonar_range > min_laser_range) {
1181         sonar_range = min_laser_range;
1182     }
1183
1184     /* Update grid */
1185
1186     angle = sonar_theta * M_DEG2RAD;
1187
1188     sonar_dir[0] = cos(angle);
1189     sonar_dir[1] = sin(angle);
1190     sonar_dir[2] = 0.0;
1191
1192     sonar_pos[0] = sonar_dir[0] * SONAR_RAD + sonar_x;
1193     sonar_pos[1] = sonar_dir[1] * SONAR_RAD + sonar_y;
1194     sonar_pos[2] = SONAR_HEIGHT + HEIGHT_OFFSET;
1195
1196     if ((reading != MAX_SONAR_READING) && (sonar_range <=
1197 MAX_SONAR_RANGE)){
1198         if (sonar_range <= MAX_SONAR_OCC_RANGE) {
1199             AddCylReading(sonar_range, sonar_pos, sonar_dir, smd, map);
1200         }
1201         else {
1202             AddCylReading(sonar_range, sonar_pos, sonar_dir, clear_smd, map);
1203         }
1204     }
1205     else {
1206         AddCylReading(MAX_SONAR_RANGE, sonar_pos, sonar_dir, clear_smd,
1207 map);
1208     }
1209 }
1210
1211 void clear_robot(Map3D map, int rx, int ry)
1212 {

```

```

1213     /* Set grid cells under robot to be unoccupied */
1214
1215     double wx, wy;                /* Robot location (world/feet) */
1216     int lx, ly, lz, hx, hy, hz;   /* Corners of robot bounding
1217 box */
1218     int cx, cy, cz;               /* Grid cell coordinates */
1219
1220
1221     wx = (double) rx / 120.0;
1222     wy = (double) ry / 120.0;
1223
1224     if (world2grid(map, wx - ROBOT_RADIUS, wy - ROBOT_RADIUS, 0.0,
1225         &lx, &ly, &lz) == -1) {
1226         printf("clear_robot: robot edge (%f, %f, %f) out of range.\n",
1227             wx - ROBOT_RADIUS, wy - ROBOT_RADIUS, 0.0);
1228         return;
1229     }
1230     if (world2grid(map, wx + ROBOT_RADIUS, wy + ROBOT_RADIUS,
1231 ROBOT_HEIGHT,
1232         &hx, &hy, &hz) == -1) {
1233         printf("clear_robot: robot edge (%f, %f, %f) out of range.\n",
1234             wx + ROBOT_RADIUS, wy + ROBOT_RADIUS, ROBOT_HEIGHT);
1235         return;
1236     }
1237
1238     for (cx = lx; cx <= hx; cx++) {
1239         for (cy = ly; cy <= hy; cy++) {
1240             for (cz = lz; cz <= hz; cz++) {
1241                 set_grid(map, cx, cy, cz, NEG);
1242             }
1243         }
1244     }
1245 }
1246
1247 void grid_clear(Map3D grid)
1248 /*
1249     Clear current grid;
1250 */
1251 {
1252     ClearMap3D(grid);
1253 }
1254
1255
1256 void grid_decay(Map3D grid)
1257 /*
1258     Decay grid cells towards base probability
1259 */
1260 {
1261     int k, km;
1262
1263     km =
1264 1<<((ILOG2C(grid.msize[ 0 ]) + ILOG2C(grid.msize[ 1 ]) + ILOG2C(grid.msize[ 2 ]));
1265
1266     for (k=0; k<km; k++) {
1267         if (grid.mapm[ k] != 0) {
1268             if (grid.mapm[ k] > GRID_DECAY) {
1269                 grid.mapm[ k] -= GRID_DECAY;
1270             }

```



```

1271         else if (grid.mapm[ k] < -GRID_DECAY) {
1272             grid.mapm[ k] += GRID_DECAY;
1273         }
1274         else {
1275             grid.mapm[ k] = 0;
1276         }
1277     }
1278 }
1279
1280 void grid_translate(Map3D grid1, Map3D grid2, double dx, double dy)
1281 /*
1282  Translate all cells in <grid1> by <dx, dy> (feet) and store results in
1283  <grid2>
1284  */
1285 {
1286     double wx, wy, wz;          /* World coords */
1287     int x, y, z;                /* Initial grid cell coordinates */
1288     int trans_index;            /* Transformed cell index */
1289
1290     printf("Translating by (%f, %f)\n", dx, dy);
1291
1292     printf("Initial grid\n");
1293     grid_display(grid1, SONAR_HEIGHT, 0.0, 0.0);
1294     printf("Hit <return>\n");
1295     getchar();
1296
1297     grid_clear(grid2);
1298
1299     for (x = 0; x < grid1.msize[ 0]; x++) {
1300         for (y = 0; y < grid1.msize[ 1]; y++) {
1301             for (z = 0; z < grid1.msize[ 2]; z++) {
1302                 grid2world(grid1, x, y, z, &wx, &wy, &wz);
1303                 trans_index = world2index(grid1, wx + dx, wy + dy, wz);
1304                 if (trans_index != -1) {
1305                     grid2.mapm[ trans_index] =
1306                         grid1.mapm[ grid2index(grid1, x, y, z)];
1307                 }
1308             }
1309         }
1310     }
1311
1312     printf("Translated grid\n");
1313     grid_display(grid2, SONAR_HEIGHT, 0.0, 0.0);
1314     printf("Hit <return>\n");
1315     getchar();
1316 }
1317
1318 void grid_rotate(Map3D grid1, Map3D grid2, double dtheta)
1319 /*
1320  Translate all cells in <grid1> by <dtheta> (degrees) and store results
1321  in
1322  <grid2>
1323  */
1324 {
1325     double wx, wy, wz;          /* Cartesian world coords of initial point
1326     */
1327     double rx, ry;              /* Rotated Cartesian coords */

```

```

1329     double dx, dy;                /* Cartesian vector from center to point
1330 */
1331     double radtheta;               /* Rotation in radians */
1332     double r, theta;               /* Polar coords from center to point */
1333     int x, y, z;                   /* Initial grid cell coordinates */
1334     int trans_index;               /* Transformed cell index */
1335
1336     printf("Rotating by (%f)\n", dtheta);
1337
1338     radtheta = dtheta * M_DEG2RAD;
1339
1340     printf("Initial grid\n");
1341     grid_display(grid1, SONAR_HEIGHT, 0.0, 0.0);
1342     printf("Hit <return>\n");
1343     getchar();
1344
1345     grid_clear(grid2);
1346
1347     for (x = 0; x < grid1.msize[0]; x++) {
1348         for (y = 0; y < grid1.msize[1]; y++) {
1349             for (z = 0; z < grid1.msize[2]; z++) {
1350                 grid2world(grid1, x, y, z, &wx, &wy, &wz);
1351
1352                 dx = wx - grid1.cx;
1353                 dy = wy - grid1.cy;
1354
1355                 r = hypot(dy, dx);
1356                 theta = atan2(dy, dx);
1357
1358                 rx = grid1.cx + r * cos(theta + radtheta);
1359                 ry = grid1.cy + r * sin(theta + radtheta);
1360
1361                 trans_index = world2index(grid1, rx, ry, wz);
1362                 if (trans_index != -1) {
1363                     grid2.mapm[trans_index] =
1364                         grid1.mapm[grid2index(grid1, x, y, z)];
1365                 }
1366             }
1367         }
1368     }
1369
1370     printf("Rotated grid\n");
1371     grid_display(grid2, SONAR_HEIGHT, 0.0, 0.0);
1372     printf("Hit <return>\n");
1373     getchar();
1374 }
1375
1376
1377 double grid_match(Map3D stm, Map3D local)
1378 /*
1379     Match two (aligned) evidence grids
1380 */
1381 {
1382     double score = 0.0;            /* Match score */
1383     double wx, wy, wz;             /* World coords of match point */
1384     int x, y, z;                   /* Grid cell coordinates of match point */
1385     int stm_index;                 /* Index of cell in <stm> */
1386     int p1, p2;                   /* Corresponding probabilities */

```

```

1387     int m;                /* Match point value (log scale) */
1388     int sum = 0;          /* Sum of match points values */
1389     int total = 0;        /* Total # of known points */
1390
1391     for (x = 0; x < local.msize[ 0]; x++) {
1392         for (y = 0; y < local.msize[ 1]; y++) {
1393             for (z = 0; z < local.msize[ 2]; z++) {
1394                 p1 = local.mapm[ grid2index(local, x, y, z)];
1395                 grid2world(local, x, y, z, &wx, &wy, &wz);
1396                 stm_index = world2index(stm, wx, wy, wz);
1397                 if (stm_index != -1) {
1398                     p2 = stm.mapm[ stm_index];
1399                     total++;
1400                     if (((p1 < 0) && (p2 < 0)) ||
1401                         ((p1 > 0) && (p2 > 0)) ||
1402                         ((p1 == 0) && (p2 == 0))) {
1403                         sum++;
1404                     }
1405                 }
1406             }
1407         }
1408     }
1409
1410     score = (double) sum / (double) total;
1411     /* score = (double) sum / (double) (local.msize[ 0] * local.msize[ 1] *
1412                                local.msize[ 2]);*/
1413     /* printf("grid_match: sum = %d : score = %f\n", sum, score);*/
1414
1415     return(score);
1416 }
1417
1418 double trans_match(Map3D global, Map3D local, double *bx, double *by,
1419                   double *btheta)
1420 /*
1421  Transform and match two evidence grids
1422  */
1423 {
1424     Map3D local_t;          /* Translated local grid */
1425     Map3D local_tr;         /* Translated/rotated local grid */
1426     double score;           /* Current match score */
1427     double best_score;      /* Best match score over all transforms */
1428     double dx, dy;          /* Current translation distance */
1429     double dtheta;          /* Current rotation angle */
1430     double best_x, best_y;   /* Best current translation */
1431     double best_theta;       /* Best current rotation */
1432     double vx, vy, vtheta;   /* Transformation vector */
1433     int sx, sy;             /* Translation step counter */
1434     int stheta;             /* Rotation step counter */
1435
1436     grid_init(&local_t, local.cx, local.cy);
1437     grid_init(&local_tr, local.cx, local.cy);
1438
1439     vx = 0.0;
1440     vy = 0.0;
1441     vtheta = 0.0;
1442
1443     do {
1444         best_score = 0.0;

```

```

1445
1446     for (sx = -NUM_TRANS; sx <= NUM_TRANS; sx++) {
1447         for (sy = -NUM_TRANS; sy <= NUM_TRANS; sy++) {
1448             for (stheta = -NUM_ROT; stheta <= NUM_ROT; stheta++) {
1449                 dx = TRANS_STEP * (double) sx;
1450                 dy = TRANS_STEP * (double) sy;
1451                 dtheta = ROT_STEP * (double) stheta;
1452                 grid_translate(local, local_t, vx + dx, vy + dy);
1453                 grid_rotate(local_t, local_tr, vtheta + dtheta);
1454                 score = grid_match(global, local_tr);
1455                 printf("translation (%f, %f) / rotation (%f): score =
1456 %f\n",
1457                        dx, dy, dtheta, score);
1458                 if (score > best_score) {
1459                     best_score = score;
1460                     best_x = dx;
1461                     best_y = dy;
1462                     best_theta = dtheta;
1463                 }
1464             }
1465         }
1466     }
1467
1468     vx += best_x;
1469     vy += best_y;
1470     vtheta += best_theta;
1471
1472     printf("BEST translation (%f, %f) / rotation (%f): score = %f\n",
1473           best_x, best_y, best_theta, best_score);
1474
1475 }
1476 while((best_x != 0.0) || (best_y != 0.0) || (best_theta != 0.0));
1477
1478 *bx = vx;
1479 *by = vy;
1480 *btheta = vtheta;
1481
1482 return(best_score);
1483 }
1484
1485 void grid_copy(Map3D grid1, Map3D grid2)
1486 /*
1487  Copy <grid2> to <grid1>
1488 */
1489 {
1490     double wx, wy, wz;          /* World coords */
1491     int x, y, z;                /* Grid cell coordinates */
1492     int p;                      /* Cell occupancy probability */
1493
1494     for (x = 0; x < grid1.msize[0]; x++) {
1495         for (y = 0; y < grid1.msize[1]; y++) {
1496             for (z = 0; z < grid1.msize[2]; z++) {
1497                 grid2world(grid1, x, y, z, &wx, &wy, &wz);
1498                 grid1.mapm[grid2index(grid1, x, y, z)] =
1499                     grid2.mapm[world2index(grid2, wx, wy, wz)];
1500             }
1501         }
1502     }

```

```

1503 }
1504
1505 void grid_fine_to_coarse(Map3D fine, Map3D coarse)
1506 {
1507     double wx, wy, wz;          /* World coords */
1508     int x, y, z;                /* Grid cell coordinates */
1509     int p;                      /* Cell occupancy probability */
1510     int findex;                 /* Index of cell in fine grid */
1511     int cindex;                 /* Index of cell in coarse grid */
1512     int cx, cy, cz;
1513
1514     grid_clear(coarse);
1515
1516     for (x = 0; x < fine.msize[ 0]; x++) {
1517         for (y = 0; y < fine.msize[ 1]; y++) {
1518             for (z = 0; z < fine.msize[ 2]; z++) {
1519                 findex = grid2index(fine, x, y, z);
1520
1521                 grid2world(fine, x, y, z, &wx, &wy, &wz);
1522                 cindex = world2index(coarse, wx, wy, wz);
1523
1524                 world2grid(coarse, wx, wy, wz, &cx, &cy, &cz);
1525
1526                 if (fine.mapm[ findex] < 0) {
1527                     coarse.mapm[ cindex] -= F2C_CLEAR_WT;
1528                 }
1529
1530                 if (fine.mapm[ findex] > 0) {
1531                     coarse.mapm[ cindex] += F2C_OCC_WT;
1532                 }
1533
1534                 // if ((coarse.mapm[ cindex] == 0) ||
1535                 //      (coarse.mapm[ cindex] < fine.mapm[ findex])) {
1536                 //      coarse.mapm[ cindex] = fine.mapm[ findex];
1537                 //  }
1538
1539             }
1540         }
1541     }
1542 }
1543
1544 void integrate_grid(Map3D global, /* Global grid */
1545                    Map3D local, /* Local grid */
1546                    double lox, /* Local x-origin (feet) */
1547                    double loy, /* Local y-origin (feet) */
1548                    double lotheta) /* Local origin rotation (degrees)
1549 */
1550 /*
1551 Integrate <local> grid within <global> grid
1552 */
1553 {
1554     /* Note: Assumes global origin is at (0,0,0) and only handles
1555     rotations in the xy-plane */
1556
1557     double lx, ly, lz;          /* Local coords (Cartesian) */
1558     double lr, ltheta;          /* Local coords (polar) */
1559     double wx, wy, wz;          /* World coords */
1560     double ix, iy, itheta;       /* Intermediate coords */

```



```

1561     int x, y, z;                /* Grid cell coordinates */
1562     int p;                      /* Cell occupancy probability */
1563     int global_index;           /* Index of global grid cell */
1564     int local_index;           /* Index of local grid cell */
1565
1566     printf("integrate_grid: x = %f : y = %f : theta = %f\n", lox, loy,
1567 lotheta);
1568
1569     lotheta *= M_DEG2RAD;      /* Convert to radians */
1570
1571     for (x = 0; x < global.msize[0]; x++) {
1572         for (y = 0; y < global.msize[1]; y++) {
1573             for (z = 0; z < global.msize[2]; z++) {
1574
1575                 /* Convert cell index to global coords */
1576
1577                 grid2world(global, x, y, z, &wx, &wy, &wz);
1578
1579                 /* Convert global coords to local coords */
1580
1581                 ix = wx - lox;
1582                 iy = wy - loy;
1583                 itheta = atan2(iy, ix);
1584
1585                 lr = hypot(ix, iy);
1586                 ltheta = itheta - lotheta;
1587
1588                 lx = lr * cos(ltheta);
1589                 ly = lr * sin(ltheta);
1590                 lz = wz;          /* Assume z-coord is unchanged */
1591
1592                 /*printf("global (%f, %f) --> local (%f, %f)\n", wx, wy, lx,
1593 ly);*/
1594
1595                 /* Update global cell */
1596
1597                 if ((lx >= X_MIN) && (lx <= X_MAX) &&
1598                     (ly >= Y_MIN) && (ly <= Y_MAX) &&
1599                     (lz >= Z_MIN) && (lz <= Z_MAX)) {
1600                     global_index = grid2index(global, x, y, z);
1601                     local_index = world2index(local, lx, ly, lz);
1602                     global.mapm[global_index] += local.mapm[local_index];
1603
1604                     if (global.mapm[global_index] > POS) {
1605                         global.mapm[global_index] = POS;
1606                     }
1607                     else if (global.mapm[global_index] < NEG) {
1608                         global.mapm[global_index] = NEG;
1609                     }
1610                 }
1611             }
1612         }
1613     }
1614 }
1615
1616 void integrate_global_grid(Map3D global, /* Initial global grid */
1617                           Map3D global_new, /* New global grid */
1618                           double nox, /* Local x-origin (feet) */

```

```

1619             double noy,                /* Local y-origin (feet) */
1620             double notheta)            /* Local origin rotation (degrees)
1621 */
1622 /*
1623     Integrate <local> grid within <global> grid
1624 */
1625 {
1626     /* Note: Assumes global origin is at (0,0,0) and only handles
1627        rotations in the xy-plane */
1628
1629     double nx, ny, nz;                /* New global coords (Cartesian) */
1630     double nr, ntheta;                /* New Global coords (polar) */
1631     double wx, wy, wz;                /* World coords */
1632     double ix, iy, itheta;            /* Intermediate coords */
1633     int x, y, z;                      /* Grid cell coordinates */
1634     int p;                            /* Cell occupancy probability */
1635     int global_index;                 /* Index of global grid cell */
1636     int new_index;                    /* Index of new global grid cell */
1637
1638     printf("integrate_grid: x = %f : y = %f : theta = %f\n", nox, noy,
1639 notheta);
1640
1641     notheta *= M_DEG2RAD;             /* Convert to radians */
1642
1643     for (x = 0; x < global.msize[0]; x++) {
1644         for (y = 0; y < global.msize[1]; y++) {
1645             for (z = 0; z < global.msize[2]; z++) {
1646
1647                 /* Convert cell index to global coords */
1648
1649                 grid2world(global, x, y, z, &wx, &wy, &wz);
1650
1651                 /* Convert global coords to new global coords */
1652
1653                 ix = wx - nox;
1654                 iy = wy - noy;
1655                 itheta = atan2(iy, ix);
1656
1657                 nr = hypot(ix, iy);
1658                 ntheta = itheta - notheta;
1659
1660                 nx = nr * cos(ntheta);
1661                 ny = nr * sin(ntheta);
1662                 nz = wz;                /* Assume z-coord is unchanged */
1663
1664                 /*printf("global (%f, %f) --> new global (%f, %f)\n", wx, wy, nx,
1665 ny);*/
1666
1667                 /* Update global cell */
1668
1669                 if ((nx >= GLOBAL_X_MIN) && (nx <= GLOBAL_X_MAX) &&
1670                     (ny >= GLOBAL_Y_MIN) && (ny <= GLOBAL_Y_MAX) &&
1671                     (nz >= GLOBAL_Z_MIN) && (nz <= GLOBAL_Z_MAX)) {
1672                     global_index = grid2index(global, x, y, z);
1673                     new_index = world2index(global_new, nx, ny, nz);
1674                     global.mapm[global_index] += global_new.mapm[new_index];
1675
1676                     if (global.mapm[global_index] > POS) {

```

```

1677         global.mapm[ global_index] = POS;
1678     }
1679     else if (global.mapm[ global_index] < NEG) {
1680         global.mapm[ global_index] = NEG;
1681     }
1682 }
1683 }
1684 }
1685 }
1686 }
1687
1688 void save_grid(Map3D grid)                /* Evidence grid */
1689 /*
1690     Save evidence grid to file
1691 */
1692 {
1693     char filename[ 80];                  /* Save file name */
1694
1695     printf("Enter save file name ==> ");
1696     scanf(" %s", filename);
1697
1698     printf("Saving grid to <%s>.\n", filename);
1699     WriteMap3D(grid, "Evidence Grid", "", filename);
1700 }
1701
1702 void save_grid_file(Map3D grid,            /* Evidence grid */
1703                     char *filename,        /* Save file name */
1704                     char *comment)         /* File header comment */
1705 /*
1706     Save evidence grid to specified file with header comment
1707 */
1708 {
1709     printf("Saving grid to <%s>.\n", filename);
1710     WriteMap3D(grid, comment, "", filename);
1711 }
1712
1713 void load_grid(Map3D *grid)               /* Evidence grid */
1714 /*
1715     Load evidence grid from file
1716 */
1717 {
1718     char filename[ 80];                  /* Load file name */
1719     char title[ 80], footer[ 80];        /* Discarded */
1720
1721     printf("Enter load file name ==> ");
1722     scanf(" %s", filename);
1723
1724     printf("Loading grid from <%s>.\n", filename);
1725     if (ReadMap3D(filename, grid, title, footer) == 0) {
1726         printf("load_grid: Unable to load grid from <%s>.\n", filename);
1727     }
1728 }
1729
1730 int load_grid_file(Map3D *grid,           /* Evidence grid */
1731                   char *filename)         /* Load file name */
1732 /*
1733     Load evidence grid from specified file
1734 */

```

```

1735     Returns 1 if successful, 0 otherwise
1736 */
1737 {
1738     char title[ 80], footer[ 80];          /* Discarded */
1739
1740     printf("Loading grid from <%s>.\n", filename);
1741     if (ReadMap3D(filename, grid, title, footer) == 0) {
1742         printf("load_grid: Unable to load grid from <%s>.\n", filename);
1743         return (0);
1744     }
1745     return(1);
1746 }
1747
1748 int load_grid_file_com(Map3D *grid,          /* Evidence grid */
1749                        char *filename,       /* Load file name */
1750                        char *comment)        /* Comment string */
1751 /*
1752     Load evidence grid from specified file along with header comment
1753
1754     Returns 1 if successful, 0 otherwise
1755 */
1756 {
1757     char footer[ 80];          /* Discarded */
1758
1759     printf("Loading grid from <%s>.\n", filename);
1760     if (ReadMap3D(filename, grid, comment, footer) == 0) {
1761         printf("load_grid: Unable to load grid from <%s>.\n", filename);
1762         return (0);
1763     }
1764     return(1);
1765 }
1766
1767 void grid_count_occ(Map3D grid, int *occ, int *unocc)
1768 /*
1769     Count number of occupied and unoccupied cells in grid
1770 */
1771 {
1772     int x, y, z;                /* Grid cell coordinates */
1773     int xsize, ysize, zsize;    /* Grid dimensions (#cells) */
1774     int p;                     /* Cell occupancy probability */
1775
1776     xsize = grid.msize[ 0];
1777     ysize = grid.msize[ 1];
1778     zsize = grid.msize[ 2];
1779
1780     *occ = 0;
1781     *unocc = 0;
1782
1783     for (x = 0; x < xsize; x++) {
1784         for (y = 0; y < ysize; y++) {
1785             for (z = 0; z < zsize; z++) {
1786                 p = grid.mapm[ z * ysize * xsize + y * xsize + x];
1787                 if (p > 0) {
1788                     (*occ)++;
1789                 }
1790                 else if (p < 0) {
1791                     (*unocc)++;
1792                 }
1793             }
1794         }
1795     }

```

1793 }
1794 }
1795 }
1796 }

APPENDIX E. FRONTIER-BASED EXPLORATION CODE – ROBOT.H

This appendix contains the header file for the routine that controls many of the robot's basic movement behaviors.

```
1  /*
2
3  robot.h
4
5  Header file for robot class for Nomad 200 Simulator.
6  Original code by Brian Yamauchi
7
8  Modifications for SCOUT THESIS
9  By Patrick A. Hillmeyer
10
11 */
12
13 #ifndef ROBOT_H
14 #define ROBOT_H
15
16 #include "Nclient.h"
17 #include "vector.h"
18 #include "misc.h"
19 #include "grid++.h"
20
21
22
23 // BEGIN SCOUT THESIS CHANGE
24
25 // These are the conversion macros from Nomadic that accept the steering
26 and
27 // translation values as used for the Nomad 150 and 200 and calculate
28 the
29 // differential-drive axis values for the Nomad Scout.
30
31 #define ROTATION_CONSTANT    0.118597 /* inches/degree (known to 100
32 ppm) */
33
34 #define RIGHT(trans, steer)  (trans +
35 (int)((float)steer*ROTATION_CONSTANT))
36 #define LEFT(trans, steer)   (trans -
37 (int)((float)steer*ROTATION_CONSTANT))
38
39 #define scout_vm(trans, steer)  vm(RIGHT(trans, steer), LEFT(trans,
40 steer), 0)
41 #define scout_pr(trans, steer)  pr(RIGHT(trans, steer), LEFT(trans,
42 steer), 0)
43
44 // END SCOUT THESIS CHANGE
45
46
47
48 const int NUM_SONAR = 16;      // Number of sensors of each type
49 const int NUM_IR = 16;        // Actually 0 for SCOUT but leave for now
50 const int NUM_RANGE = 16;
51
52 // BEGIN SCOUT THESIS CHANGE
```

```

53  const int NUM_TOUCH = 6;    // Scout only has 6 bumper swithes
54  // END SCOUT THESIS CHANGE
55
56  const int NUM_ARC = 16;     // Number of sensor arcs
57  const int ARC_SIZE = 3;     // Number of sensors in each arc
58  const int ARC_STEP = 1;     // Interval between first sensor
59                               // in each successive arc
60  const int ARC_OFFSET = -1;  // Value of first sensor of first arc (mod
61  16)
62
63  const int SONAR_ADDR = 17;   // State index for first sonar sensor
64  const int IR_ADDR = 1;      // State index for first IR sensor
65  const int TOUCH_ADDR = 33;   // State index for touch sensors
66  const int LASER_MODE_ADDR = 42; // State index for laser mode
67
68  const int MAX_SONAR = 255;    // Maximum sonar reading
69
70  // BEGIN SCOUT THESIS CHANGE
71  const int MAX_IR = 0;        // Maximum IR reading - no IR on Scout
72  // END SCOUT THESIS CHANGE
73
74  const int MAX_RANGE = 255;    // Maximum range reading
75
76  const int SENSOR_SEP = 225;   // Separation between adjacent sensors
77                               // in degrees/10
78  // BEGIN SCOUT THESIS CHANGE
79  // this next setting for BUMPER_SEP can be left as is for now even
80  // though it is wrong for the Scout because the procedures that use
81  // it in agent.cc for recoiling from a bumper contact are not
82  implemented yet
83  // New NOTE - changed to 600 to fake out some code in robot.cc
84  // Needs a better fix though
85  const int BUMPER_SEP = 600;   // Separation between adjacent bumpers
86                               // in degrees/10
87
88
89  const int MAX_SPEED = 200;    // Maximum velocities
90  const int MAX_TURN_RATE = 300; // From Nomadic .setup file for Scouts
91
92  const int MAX_ACCEL = 300;    // Maximum accelerations
93  const int MAX_TURN_ACCEL = 500;
94
95  const int DEFAULT_SPEED = 200; // Default velocities
96  const int DEFAULT_TURN_RATE = 300; // From Nomadic .setup file for
97  Scouts
98
99  // END SCOUT THESIS CHANGE
100
101  const int DEFAULT_ACCEL = 200; // Default accelerations
102  const int DEFAULT_TURN_ACCEL = 500;
103
104  const int MOVE_TO_SPEED = 10; // Speed for moving to (x,y)
105  const int FACE_TURN_RATE = 200; // Turning rate for facing
106
107  const int MAX_CONT_TURN = 225; // Maximum turn without
108  stopping
109  const int FACE_CONT_WAIT = 10; // How long to wait for turn
110  to finish

```

```

111
112 const int ROBOT_MIN_SPEED = -200;           // Velocity limits (command)
113 const int ROBOT_MAX_SPEED = 200;
114 const int ROBOT_MIN_TURN = -100;
115 const int ROBOT_MAX_TURN = 100;
116
117 // BEGIN SCOUT THESIS CHANGE
118 // NOTE - changing no encoder parameters for now but might need to
119 //         tweak them for the Scouts
120
121 // Dead reckoning parameters
122
123 const int ENCODER_COLOR = 19;               // Color of encoder graphic
124
125 // Minimum/maximum encoder rotation increment
126 //const double ENCODER_ROTATE_MIN = 1.0;
127 //const double ENCODER_ROTATE_MAX = 1.0;
128 const double ENCODER_ROTATE_MIN = 0.9;
129 const double ENCODER_ROTATE_MAX = 1.1;
130
131 // Encoder rotation bias
132 const double ENCODER_ROTATE_BIAS = 0.0;
133 //const double ENCODER_ROTATE_BIAS = 0.001;
134
135 // Minimum/maximum encoder translation increment
136 //const double ENCODER_TRANS_MIN = 1.0;
137 //const double ENCODER_TRANS_MAX = 1.0;
138 const double ENCODER_TRANS_MIN = 0.9;
139 const double ENCODER_TRANS_MAX = 1.1;
140
141 // Encoder translation bias
142 const double ENCODER_TRANS_BIAS = 0.0;
143 //const double ENCODER_TRANS_BIAS = 0.001;
144
145 // Cartesian move parameters
146
147 const int MOVE_XY_MAX_DIST = 1200; // Maximum move (tenths inches)
148 const int MOVE_XY_MAX_ERROR = 1;   // Maximum move error (tenths
149 inches)
150
151 // END SCOUT THESIS CHANGE
152
153 // Building Axis Direction
154
155 const int AXIS = 2960;
156
157 // Arc directions
158
159 enum { FWD, FFL, FWD_LF, FLL, LF, BLL, BACK_LF, BBL,
160        BACK, BBR, BACK_RT, BRR, RT, FRR, FWD_RT, FFR };
161
162 // Timeout for movement commands
163
164 const unsigned char MOVE_TIMEOUT = 100;
165
166 // Robot class definition
167
168 class robot {

```

```

169 public:
170     int id; // Robot ID number
171     int x, y, theta, turret; // Robot encoder position
172     int actual_x, actual_y, actual_theta; // Robot actual position
173     double enc_x, enc_y, enc_theta; // Accumulators for encoder position
174
175     int bumper_offset; // Offset between base and bumpers
176
177     double trans_ctr; // Total translation since
178 localization
179     double rot_ctr; // Total rotation since localization
180
181     int origin_x, origin_y; // Room origin
182
183     int bumpers; // Bumper bit vector
184
185     vector sonar; // Sensor values
186     vector ir;
187     vector range;
188     vector touch;
189
190     vector abs_sonar; // Absolute sensor values
191     vector abs_ir;
192     vector abs_range;
193     vector abs_touch;
194
195     vector arc; // Sensor arcs
196
197     /*
198     vector sonar(NUM_SONAR); // Sensor values
199     vector ir(NUM_IR);
200     vector range(NUM_RANGE);
201     vector touch(NUM_TOUCH);
202
203     vector abs_sonar(NUM_SONAR); // Absolute sensor values
204     vector abs_ir(NUM_IR);
205     vector abs_range(NUM_RANGE);
206     vector abs_touch(NUM_TOUCH);
207
208     vector arc(NUM_ARC); // Sensor arcs
209 */
210
211     robot(void); // Constructor
212
213     void update(void); // Sensor update
214
215     void set_default_velocity(void); // Set default trans/base/turret
216 speed
217
218     void maint_err(void); // Maintain encoder error at new position
219
220     // Relative move of <speed>/10 inches forward while turning both
221 turret
222 // and base by <angle>/10 degrees (+ = ccw, - = cw)
223
224     void move(int speed, int angle);
225
226     // Relative move of <speed>/10 inches forward

```

```

227
228 void fwd(int speed);
229
230 // Turn base by <angle>/10 degrees (+ = ccw, - = cw)
231
232 void turn(int angle);
233
234 // Set origin to current position
235
236 void set_origin_here(void);
237
238 // Set origin to (o_x, o_y)
239
240 void set_origin_loc(int o_x, int o_y);
241
242 // Convert angle to sensor index
243
244 int theta2sensor(double theta);
245
246 // Convert sensor index to angle
247
248 double sensor2theta(int sensor);
249
250 // Return 1 if all range sensors in an arc <width> x 2 sensors wide
251 // centered around sensor <ctr> return greater or equal to <dist>,
252 // 0 otherwise.
253
254 int check_clear(int ctr, int width, int dist);
255
256 // Wrap index to [ 0..NUM_SENSORS]
257
258 int sensor_wrap(int index);
259
260 // Turn off sensors
261
262 void shutdown(void);
263
264 // Move robot to <x, y> (world coords, tenths of inch)
265
266 int move_to_xy(int cx, int cy);
267
268 // Turn robot to face <angle> accurately
269
270 void face_angle(int angle);
271
272 // Turn robot to face <angle> quickly
273
274 void face_angle_fast(int angle);
275
276 // Turn robot to face <angle> quickly, without stopping
277
278 void face_angle_cont(int angle);
279
280 // Align turret with base
281
282 void turret_align(void);
283
284 // Relative Cartesian move to <x, y> (world coords, tenths of inches)

```



```

285
286 void move_rel(int x, int y);
287
288 // Sensor functions
289
290 void sonar_on(void);
291 void sonar_single(int index);           // Index of sensor to fire
292 void sonar_off(void);
293 void ir_on(void);
294 void ir_single(int index);             // Index of sensor to fire
295 void ir_off(void);
296 void laser_on(void);
297 void laser_off(void);
298
299 // Wait for the robot to start moving (any motor)
300
301 void wait_start(void);
302
303 private:
304
305 // Initialization functions
306
307 void initialize_sensors(void);
308
309 // Update functions
310
311 void update_dr(void);
312 void update_range_arcs(void);
313 void update_arc(int &av, int first, int last);
314
315 // Cleanup functions
316 void deactivate_sonar(void);
317
318
319 };
320
321 #endif

```

APPENDIX F. FRONTIER-BASED EXPLORATION CODE – ROBOT.CC

This appendix contains the source code for the routine that controls many of the robot's basic movement behaviors.

```
1  /*
2
3  robot.cc
4
5  Robot class for Nomad 200 Simulator.
6  Original code by Brian Yamauchi
7
8  Modifications for SCOUT THESIS
9  By Patrick A. Hillmeyer
10
11 */
12
13 #include <iostream.h>
14 #include <math.h>
15
16 #include "robot.h"
17 #include "drand.h"
18 #include "irand.h"
19
20 // Dead reckoning mode (actual, independent, or error)
21
22 #define DR_ACTUAL
23
24 // Touch vector mask
25
26 const int touch_mask[20] = { 1, 2, 4, 8, 16,
27                               32, 64, 128, 256, 512,
28                               1024, 2048, 4096, 8192, 16384,
29                               32768, 65536, 131072, 262144, 524288 };
30
31 // Forward contact mask
32
33 const int FWD_CONTACT = 1015839;
34
35 robot::robot(void):sonar(NUM_SONAR), ir(NUM_IR), range(NUM_RANGE),
36                     touch(NUM_TOUCH), abs_sonar(NUM_SONAR),
37                     abs_ir(NUM_IR),
38                     abs_range(NUM_RANGE), abs_touch(NUM_TOUCH),
39                     arc(NUM_ARC)
40 {
41     int rx, ry, rtheta;          // Robot home position (1/10 inch, 1/10
42     degree)
43
44     // Connect to server and activate all sensors
45
46     cout << "Enter Nserver host name ==> ";
47     cin >> SERVER_MACHINE_NAME;
48
49     cout << "Enter Nserver robot ID ==> ";
50     cin >> id;
51
52     connect_robot(id);
```

```

53 initialize_sensors();
54 set_default_velocity();
55
56 // Initialize origin
57
58 origin_x = 0;
59 origin_y = 0;
60
61 // Initialize translation/rotation counters
62
63 trans_ctr = 0.0;
64 rot_ctr = 0.0;
65
66 // Zero the robot
67
68 // zr();
69
70 // Set robot initial position
71
72 // tk("Align me.");
73
74 cout << "Enter robot x y theta (no commas) ==> ";
75 cin >> rx >> ry >> rtheta;
76
77 gs();
78 bumper_offset = State[ 36] - rtheta;
79
80 place_robot(rx, ry, rtheta, rtheta);
81
82 // Initialize actual position
83
84 gs();
85 actual_x = State[ 34] ;
86 actual_y = State[ 35] ;
87 actual_theta = State[ 36] ; // DR heading
88 // actual_theta = 3600 - wrap(State[ 43] - AXIS, 0, 3600); // Compass
89 heading
90
91 // Initialize encoder accumulators
92
93 enc_x = (double) actual_x;
94 enc_y = (double) actual_y;
95 enc_theta = (double) actual_theta;
96
97 // Initialize estimated position
98
99 x = round(enc_x);
100 y = round(enc_y);
101 theta = round(enc_theta);
102
103 // Display robot estimated position
104
105 // draw_robot(x, y, theta, theta, ENCODER_COLOR);
106
107 // Updater robot state
108
109 update();
110 }

```

```

111
112 void robot::maint_err(void)
113 {
114     // Maintain encoder error at new position
115
116     int ex, ey, etheta;
117
118     ex = x - actual_x;
119     ey = y - actual_y;
120     etheta = theta - actual_theta;
121
122     gs();
123     place_robot(State[ 34] , State[ 35] , State[ 36] , State[ 37] );
124
125     actual_x = State[ 34] ;
126     actual_y = State[ 35] ;
127     actual_theta = State[ 36] ;
128
129     x = actual_x + ex;
130     y = actual_y + ey;
131     theta = actual_theta + etheta;
132 }
133
134 void robot::set_default_velocity()
135 {
136     sp(DEFAULT_SPEED, DEFAULT_TURN_RATE, 0); // TEMP FIX for SCOUT
137     ac(DEFAULT_ACCEL, DEFAULT_TURN_ACCEL, 0); // TEMP FIX for SCOUT
138 }
139
140 void robot::update(void)
141 {
142     // Update values for position <x, y, theta>, sonar <sonar>, infrared
143     // sensors <ir>. Also update range arcs.
144
145     int range_offset; // Rotation offset for range sensors
146     int touch_offset; // Rotation offset for touch sensors
147     int i;
148
149     gs();
150
151     update_dr();
152
153     range_offset = (int) ((double) theta / (double) SENSOR_SEP + 0.5);
154
155     // NOTE - need to fix this BUMPER_SEP dependency later for SCOUT
156
157     touch_offset = wrap((int) ((double) (theta + bumper_offset)
158                             / (double) BUMPER_SEP + 0.5),
159                         NUM_TOUCH);
160
161     // cout << "Offset = " << range_offset << " " << endl;
162
163     for (i = 0; i < NUM_SONAR; i++) {
164         sonar[ i ] = State[ i + SONAR_ADDR] ;
165         abs_sonar[ i ] = State[ wrap(i - range_offset, NUM_SONAR) +
166 SONAR_ADDR] ;
167

```

```

168         //      cout << "i = " << i << " : range_offset i = " << wrap(i -
169 range_offset, NUM_SONAR) <<
170         //      " : sonar[" << i << "]" = " << sonar[i] << "" << endl;
171     }
172
173     // BEGIN SCOUT THESIS CHANGE
174     // Comment out IR code and only depend on sonars
175
176     // SCOUT THESIS CHANGE - correct error where sensor updates below were
177     left out of loop
178     for (i = 0; i < NUM_SONAR; i++) {
179         abs_range[i] = abs_sonar[i];
180         range[i] = sonar[i];
181         // cout << "Just set by sonar[i] value : range[" << i << "]" = " <<
182         range[i]
183         //      << endl;          // TEMP FIX
184         // cout << "Just set by abs_sonar[i] value : abs_range[" << i << "]" = "
185         //      << abs_range[i] << endl;          // TEMP FIX
186
187     } // end for loop
188
189     // for (i = 0; i < NUM_IR; i++) {
190     //     ir[i] = State[i + IR_ADDR];
191     //     abs_ir[i] = State[wrap(i - range_offset, NUM_IR) + IR_ADDR];
192
193     //     cout << "i = " << i << " : range_offset i = " << wrap(i -
194     range_offset, NUM_IR) <<
195     //     " : ir[" << i << "]" = " << ir[i] << "" << endl;
196     // }
197
198     // for (i = 0; i < NUM_RANGE; i++) {
199     //     if (abs_ir[i] < abs_sonar[i]) {
200     //         abs_range[i] = abs_ir[i];
201     //     }
202     //     else {
203     //         abs_range[i] = abs_sonar[i];
204     //     }
205     //
206     //     if (ir[i] < sonar[i]) {
207     //         range[i] = ir[i];
208     //     }
209     //     else {
210     //         range[i] = sonar[i];
211     //     }
212     // }
213
214     // END SCOUT THESIS CHANGE
215
216     for (i = 0; i < NUM_RANGE; i++) {
217         if (range[i] > MAX_RANGE) {
218             range[i] = MAX_RANGE;
219         // cout << "Compared against MAX_RANGE : range[" << i << "]" = " <<
220         range[i]
221         //      << endl;          // TEMP FIX
222         }
223         if (abs_range[i] > MAX_RANGE) {
224             abs_range[i] = MAX_RANGE;

```



```

225 // cout << "Compared against MAX_RANGE : abs_range[" << i << "]" = " <<
226 abs_range[ i]
227 //      << endl;      // TEMP FIX
228 }
229 } // end for loop
230
231 update_range_arcs();
232
233 bumpers = State[ TOUCH_ADDR ] ;
234 // if (bumpers != 0) {
235 //     cout << "Bumper state = " << bumpers << " " << endl;
236 // }
237
238 // NOTE - touch_offset depends on BUMPER_SET - needs fix for SCOUT
239
240 for (i = 0; i < NUM_TOUCH; i++) {
241     if (bumpers &
242         touch_mask[ wrap(i + touch_offset, NUM_TOUCH)] ) {
243         touch[ i ] = 1;
244         cout << "Contact on bumper " << i << " (abs index = " <<
245             wrap(i + touch_offset, NUM_TOUCH) << " )" << endl;
246     }
247     else {
248         touch[ i ] = 0;
249     }
250 }
251
252 // cout << "Sonar = " << sonar << endl;      // TEMP FIX
253 // cout << "IR = " << ir << endl;
254 // cout << "Range = " << range << endl;      // TEMP FIX
255 // cout << "Arcs = " << arc << endl;      // TEMP FIX
256 // cout << "Touch = " << touch << endl;
257 }
258
259 void robot::update_dr(void)
260 {
261     // Update dead reckoning
262
263     double dx, dy, dtheta;           // Motion since last update
264     int dtheta_mag;                  // Magnitude of rotation
265     int dtheta_sgn;                  // Direction of rotation (+ ccw, - cw)
266
267     double vec_r, vec_theta;         // Motion vector
268     double inc;                      // Motion increment
269     double ctheta, stheta;           // Components along x-axis and y-
270     axis
271     double trans_step;               // Length of current translation
272     step
273
274     int i;
275
276     dx = (double) (State[ 34 ] - actual_x);
277     dy = (double) (State[ 35 ] - actual_y);
278     dtheta = angle_sgn_diff((double) State[ 36 ] / 10.0,
279                             (double) actual_theta / 10.0) * 10.0;
280
281     actual_x = State[ 34 ] ;
282     actual_y = State[ 35 ] ;

```

```

283     actual_theta = State[ 36];    // DR heading
284 //  actual_theta = 3600 - wrap(State[ 43] - AXIS, 0, 3600);    // Compass
285 heading
286
287 #ifdef DR_ACTUAL
288
289     // Dead reckoning always returns actual position
290
291     x = actual_x;
292     y = actual_y;
293     theta = actual_theta;
294 // SCOUT THESIS CHANGE - comment out original turret line
295 // set turret to be same as SCOUT heading angle
296 //  turret = State[ 37];
297     turret = theta;
298
299 #endif // DR_ACTUAL
300
301 #ifdef DR_INDEP
302
303     // Dead reckoning is updated by actual displacements, but may be set
304     // independently
305
306     draw_robot(x, y, theta, theta, ENCODER_COLOR);
307
308     x += (int) dx;
309     y += (int) dy;
310     theta += (int) dtheta;
311
312     draw_robot(x, y, theta, theta, ENCODER_COLOR);
313
314 #endif // DR_INDEP
315
316 #ifdef DR_ERROR
317
318     // Dead reckoning accumulates error over time
319
320     draw_robot(x, y, theta, theta, ENCODER_COLOR);
321
322     rot_ctr += fabs(dtheta);
323
324     dtheta_mag = (int) fabs(dtheta);
325     dtheta_sgn = sgn(dtheta);
326     for (i = 0; i < dtheta_mag; i++) {
327         enc_theta += (double) dtheta_sgn *
328             rdrand(ENCODER_ROTATE_MIN, ENCODER_ROTATE_MAX) +
329             ENCODER_ROTATE_BIAS;
330     }
331     enc_theta = angle_wrap(enc_theta / 10.0) * 10.0;
332
333     theta = round(enc_theta);
334
335     vec_r = hypot(dx, dy);
336
337     if (vec_r > 0.0) {
338         trans_ctr += vec_r;
339
340         vec_theta = (double) theta / 10.0;

```

```

341     if (angle_diff(vec_theta, atan2(dy, dx) * RAD2DEG) > 90.0) {
342         vec_theta = angle_wrap(vec_theta + 180.0);
343     }
344
345     ctheta = cos(vec_theta * DEG2RAD);
346     stheta = sin(vec_theta * DEG2RAD);
347
348     for (i = 0; i < (int) vec_r; i++) {
349         trans_step = rdrand(ENCODER_TRANS_MIN, ENCODER_TRANS_MAX) +
350             ENCODER_TRANS_BIAS;
351         trans_step = 1.0;
352         enc_x += ctheta * trans_step;
353         enc_y += stheta * trans_step;
354     }
355
356     enc_x += ctheta * (vec_r - (int) vec_r);
357     enc_y += stheta * (vec_r - (int) vec_r);
358
359     x = round(enc_x);
360     y = round(enc_y);
361 }
362
363 draw_robot(x, y, theta, theta, ENCODER_COLOR);
364
365 /* cout << "Actual: (" << actual_x << ", " << actual_y << ") <<
366 actual_theta
367 << "> -- Encoder: (" << enc_x << ", " << enc_y << ") << enc_theta
368 <<
369 "> -- Error: (" << enc_x - (double) actual_x << ", " <<
370 enc_y - (double) actual_y << ") <<
371 round(angle_sgn_diff(enc_theta / 10.0,
372                     (double) actual_theta / 10.0)
373 * 10.0) << ">" << endl;
374
375 cout << "Total: translation = " << trans_ctr << " : rotation = " <<
376 rot_ctr << endl;*/
377
378 #endif // DR_ERROR
379
380 return;
381 }
382
383 void robot::update_range_arcs(void)
384 {
385     // Update range arcs. The value of the arc is equal to the minimum
386     // range reading of a sensor that is included in that arc.
387
388     int i, first, last;
389
390     for (i = 0; i < NUM_ARC; i++) {
391         first = wrap(i * ARC_STEP + ARC_OFFSET, NUM_RANGE);
392         last = wrap(first + ARC_SIZE - 1, NUM_RANGE);
393
394         arc[i] = range.min(first, last);
395     }
396 }
397
398 void robot::sonar_on(void)

```

```

399 {
400     // Activate all sonar sensors
401
402     int sn_order[ 16];    // Sonar firing order
403
404     /* set firing rate and sequence of all sonar */
405     sn_order[ 0] = 0; sn_order[ 1] = 10; sn_order[ 2] = 6;
406     sn_order[ 3] = 14; sn_order[ 4] = 2; sn_order[ 5] = 12;
407     sn_order[ 6] = 4; sn_order[ 7] = 9; sn_order[ 8] = 1;
408     sn_order[ 9] = 13; sn_order[ 10] = 5; sn_order[ 11] = 15;
409     sn_order[ 12] = 7; sn_order[ 13] = 11; sn_order[ 14] = 3;
410     sn_order[ 15] = 8;
411     conf_sn (10, sn_order);    // TEMP FIX SET LONGER SONAR FIRING TIME
412 }
413
414 void robot::sonar_single(int index) // Index of sensor to fire
415 {
416     // Activate one sonar sensor
417
418     int sn_order[ 16];    // Sonar firing order
419
420     sn_order[ 0] = index;
421     sn_order[ 1] = 255;
422
423     conf_sn (12, sn_order);
424 }
425
426 void robot::sonar_off(void)
427 {
428     // Deactivate all sonar sensors
429
430     int sn_order[ 16];    // Sonar firing order
431
432     sn_order[ 0] = 255;
433     conf_sn(1, sn_order);
434 }
435
436
437 // BEGIN SCOUT THESIS CHANGE
438 // let the IRs and laser be configured - just comment out the activation
439 // in the following procedures
440
441 void robot::ir_on(void)
442 {
443     // Activate all IR sensors
444
445     int ir_order[ 16];    // IR firing order
446
447     /* set firing rate and sequence of all IR */
448     ir_order[ 0] = 0; ir_order[ 1] = 10; ir_order[ 2] = 6;
449     ir_order[ 3] = 14; ir_order[ 4] = 2; ir_order[ 5] = 12;
450     ir_order[ 6] = 4; ir_order[ 7] = 9; ir_order[ 8] = 1;
451     ir_order[ 9] = 13; ir_order[ 10] = 5; ir_order[ 11] = 15;
452     ir_order[ 12] = 7; ir_order[ 13] = 11; ir_order[ 14] = 3;
453     ir_order[ 15] = 8;
454     // conf_ir (2, ir_order);
455 }
456

```

```

457 void robot::ir_single(int index)    // Index of sensor to fire
458 {
459     // Activate one IR sensor
460
461     int ir_order[ 16];    // IR firing order
462
463     ir_order[ 0] = index;
464     ir_order[ 1] = 255;
465
466     // conf_ir(2, ir_order);
467 }
468
469 void robot::ir_off(void)
470 {
471     // Deactivate all IR sensors
472
473     int ir_order[ 16];    // IR firing order
474
475     ir_order[ 0] = 255;
476     // conf_ir(2, ir_order);
477 }
478
479 void robot::laser_on(void)
480 {
481     // Activate laser
482
483     // conf_ls(LASER_MODE_ON, THRESHHOLD, WIDTH, NUMDATA, AVG);
484 }
485
486 void robot::laser_off(void)
487 {
488     // Deactivate laser
489
490     // conf_ls(LASER_MODE_OFF, THRESHHOLD, WIDTH, NUMDATA, AVG);
491 }
492
493 void robot::initialize_sensors(void)
494 {
495     /*
496         Activate all robot sensors
497     */
498     // static int ir_on[ 16] ={ 0, 10, 6, 14, 2, 12, 4, 9, 1, 13, 5, 15, 7,
499     11, 3, 8};
500     // static int ir_off[ 16]={ 255, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,
501     13, 14, 15};
502
503     static int sn_on[ 16] ={ 0, 10, 6, 14, 2, 12, 4, 9, 1, 13, 5, 15, 7,
504     11, 3, 8};
505     static int sn_off[ 16]={ 255, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,
506     13, 14, 15};
507
508     int i;
509
510     /* init_sensors(); */
511
512     // conf_ir(0, ir_on);
513     conf_sn(10, sn_on); //TEMP FIX - set longer slower firing time
514

```



```

515     Smask[ 42] = 1;
516 //     conf_ls(LASER_MODE_ON, THRESHHOLD, WIDTH, NUMDATA, AVG);
517
518     /*     conf_cp(1); */ /* ==--== doesn't work with Ndirect.o */
519
520     posDataRequest(POS_SONAR);           // Just get the sonar data for
521 the SCOUT
522     if (posDataCheck() != (POS_SONAR)) {           // Just check for the
523 sonar data for the SCOUT
524         cout << "\nERROR: Could not set up pose info for sensors.\n";
525         exit(-1);
526     }
527 }
528
529 // END SCOUT THESIS CHANGE
530
531
532
533 void robot::move(int speed, int angle)
534 {
535     // Relative move of <speed>/10 inches forward while turning
536     // base and turret by <angle>/10 degrees (+ = ccw, - = cw)
537
538     int vel_speed, vel_angle;    // Velocity commands
539
540     vel_speed = limit(speed, ROBOT_MIN_SPEED, ROBOT_MAX_SPEED);
541     vel_angle = limit(angle, ROBOT_MIN_TURN, ROBOT_MAX_TURN);
542
543     // BEGIN SCOUT THESIS CHANGE
544     scout_vm(vel_speed, vel_angle);
545
546     // scout_pr(speed, angle);
547 }
548
549 void robot::fwd(int speed)
550 {
551     // Relative move of <speed>/10 inches forward
552
553     // TEMP SCOUT FIX- change pr cmds to vm cmds and comment out the wait
554     scout_vm(speed, 0);
555     // ws(1, 1, 0, 5);    TEMP FIX - comment out the wait
556 }
557
558 void robot::turn(int angle)
559 {
560     // Turn base and turret by <angle>/10 degrees (+ = ccw, - = cw)
561
562     // TEMP FIX - change pr cmds to vm cmds and comment out the wait
563     scout_vm(0, angle);
564     // ws(1, 1, 0, 5);    TEMP FIX - comment out the wait
565 }
566
567 // END SCOUT THESIS CHANGE
568
569
570 void robot::set_origin_here(void)
571 {
572     // Define current position and orientation as origin

```

```

573
574 /* dp(0, 0);
575 da(0, 0);*/
576
577 origin_x = State[ 34] ;
578 origin_y = State[ 35] ;
579
580 x = 0;
581 y = 0;
582 theta = 0;
583
584 cout << "Setting origin to (" << origin_x << ", " << origin_y << ")."
585 << endl;
586 }
587
588 void robot::set_origin_loc(int o_x, int o_y)
589 {
590     // Define new origin relative to current origin
591
592     origin_x += o_x;
593     origin_y += o_y;
594
595     x = 0;
596     y = 0;
597     theta = 0;
598
599     cout << "Setting origin to (" << origin_x << ", " << origin_y << ")."
600     << endl;
601 }
602
603 int robot::theta2sensor(double theta)
604 {
605     // Convert angle to sensor index
606
607     int sensor;
608
609     sensor = (int) (theta * 10.0) / SENSOR_SEP;
610     return(sensor);
611 }
612
613 double robot::sensor2theta(int sensor)
614 {
615     // Convert sensor index to angle
616
617     double theta;
618
619     theta = (double) (sensor * SENSOR_SEP) / 10.0;
620     return(theta);
621 }
622
623 int robot::sensor_wrap(int index)
624 {
625     // Wrap index to [ 0..NUM_RANGE]
626
627     int windex;
628
629     windex = wrap(index, NUM_RANGE);
630     return(windex);

```

```

631 }
632
633 int robot::check_clear(int ctr, int width, int dist)
634 {
635     // Return 1 if all range sensors in an arc <width> x 2 sensors wide
636     // centered around sensor <ctr> return greater or equal to <dist>,
637     // 0 otherwise.
638
639     int left, right;
640     int min_dist;
641
642     left = sensor_wrap(ctr + width);
643     right = sensor_wrap(ctr - width);
644
645     min_dist = range.min(right, left);
646
647     if (min_dist >= dist) {
648         return(1);
649     }
650     else {
651         return(0);
652     }
653 }
654
655 void robot::shutdown(void)
656 {
657     sonar_off();
658     ir_off();
659     laser_off();
660 }
661
662 int robot::move_to_xy(int cx, int cy)
663 {
664     // Move robot to <x, y> (world coords, tenths of inch)
665
666     int dx, dy;          // Difference between current and desired
667     positions            //
668     double dist;         // Distance to destination
669     double angle;        // Bearing to destination
670     double mturn;        // Turn command
671
672     // BEGIN SCOUT THESIS CHANGE
673     scout_vm(0, 0);
674     // END SCOUT THESIS CHANGE
675     sp(MOVE_TO_SPEED, DEFAULT_TURN_RATE, 0); // TEMP FIX for SCOUT
676
677     update();
678
679     cout << "current position (" << x << ", " << y << ") : destination
680 ("
681     << cx << ", " << cy << ")" << endl;
682
683     dx = cx - x;
684     dy = cy - y;
685
686     dist = hypot((double) dx, (double) dy);
687     if (dist == 0.0) {
688         angle = 0.0;

```

```

689     }
690     else {
691         angle = atan2((double) dy, (double) dx) * RAD2DEG;
692     }
693
694     cout << "distance = " << dist << " : angle = " << angle << endl;
695
696     while((dist > MOVE_XY_MAX_ERROR) && (touch.max(0, NUM_TOUCH - 1) ==
697 0)) {
698         if (dist > MOVE_XY_MAX_DIST) {
699             cout << "Destination too far (" << dist / 10.0 << " inches)"
700 <<
701             endl;
702             return(0);
703         }
704
705         mturn = (int) (angle_sgn_diff(angle, (double) theta / 10.0) *
706 10.0);
707         // BEGIN SCOUT THESIS CHANGE
708
709         // TEMP FIX - change pr cmds to vm cmds and comment out the ws cmds
710         scout_vm(0, (int) mturn);
711         // ws(1, 1, 0, 100); TEMP FIX - comment out wait
712
713         scout_vm((int) dist, 0);
714         // ws(1, 1, 0, 100); TEMP FIX - comment out wait
715
716         // END SCOUT THESIS CHANGE
717
718         update();
719
720         cout << "current position (" << x << ", " << y << ") : destination
721 ("
722         << cx << ", " << cy << ")" << endl;
723
724         dx = cx - x;
725         dy = cy - y;
726
727         dist = hypot((double) dx, (double) dy);
728         if (dist == 0.0) {
729             angle = 0.0;
730         }
731         else {
732             angle = atan2((double) dy, (double) dx) * RAD2DEG;
733         }
734
735         cout << "distance = " << dist << " : angle = " << angle << endl;
736     }
737
738     set_default_velocity();
739
740     return(1);
741 }
742
743 void robot::face_angle(int angle) // Desired angle (1/10 degree)
744 {
745     // Turn robot to face <angle> accurately
746

```

```

747     int dtheta;           // Difference between current and desired angle
748
749     cout << "Facing angle <" << angle << ">" << endl;
750
751     // BEGIN SCOUT THESIS CHANGE
752
753     scout_vm(0, 0);
754     sp(DEFAULT_SPEED, FACE_TURN_RATE, 0); // TEMP FIX for SCOUT
755
756     update();
757     dtheta = (int)
758         (angle_sgn_diff((double) angle / 10.0, (double) theta / 10.0) *
759         10.0);
760
761     while(dtheta != 0) {
762         cout << "current angle = " << theta << " : turn = " << dtheta <<
763         endl;
764
765         // TEMP FIX - change below to vm vice pr and comment out the wait
766         scout_vm(0, dtheta);
767         // ws(1, 1, 0, 100); TEMP FIX comment out the wait
768
769         // END SCOUT THESIS CHANGE
770
771         update();
772         dtheta = (int)
773             (angle_sgn_diff((double) angle / 10.0, (double) theta / 10.0) *
774             10.0);
775     }
776
777     cout << "Alignment complete." << endl;
778
779     set_default_velocity();
780 }
781
782 void robot::face_angle_fast(int angle) // Desired angle (1/10 degree)
783 {
784     // Turn robot to face <angle> quickly
785
786     int dtheta;           // Difference between current and desired angle
787
788     dtheta = (int)
789         (angle_sgn_diff((double) angle / 10.0, (double) theta / 10.0) *
790         10.0);
791
792     // TEMP FIX for SCOUT to line below
793     // cout << "face_angle_fast(" << angle << ") : scout_vm(0, " << dtheta
794     // << ")" << endl; // TEMP FIX for SCOUT
795
796     // BEGIN SCOUT THESIS CHANGE
797
798     // TEMP FIX - change pr cmds to vm cmds and comment out the wait
799     scout_vm(0, dtheta);
800     // ws(1, 1, 0, 10); TEMP FIX - comment out the wait
801     // END SCOUT THESIS CHANGE
802 }
803
804 void robot::face_angle_cont(int angle) // Desired angle (1/10 degree)

```



```

805 {
806     // Turn robot to face <angle> quickly, without stopping
807
808     int dtheta;           // Difference between current and desired angle
809
810     dtheta = (int)
811         (angle_sgn_diff((double) angle / 10.0, (double) theta / 10.0) *
812         10.0);
813
814     cout << "face_angle_cont(" << angle << ") : pr(0, " << dtheta << ", "
815         << dtheta << ")" << endl;
816
817     if ((dtheta < -MAX_CONT_TURN) || (dtheta > MAX_CONT_TURN)) {
818         // mv(MV_VM, 0, MV_PR, dtheta, MV_PR, dtheta); // TEMP FIX - comment
819         this line out
820         mv(MV_VM, 0, MV_PR, dtheta, MV_IGNORE, 0); // TEMP FIX - try to fix
821         SCOUT problem
822         ws(1, 1, 0, FACE_CONT_WAIT); // wait for both wheels to stop for
823         SCOUT
824     }
825     else {
826         // mv(MV_IGNORE, 0, MV_PR, dtheta, MV_PR, dtheta); // TEMP FIX -
827         comment this line out
828         mv(MV_IGNORE, 0, MV_PR, dtheta, MV_IGNORE, 0); // TEMP FIX - try
829         to fix SCOUT problem
830     }
831 }
832
833 // BEGIN SCOUT THESIS CHANGE
834 // do not need this next routine because there is no separate
835 // turret to align on the SCOUT
836 // leave as is because call to turret_align has been commented out
837 // in agent.cc
838 void robot::turret_align(void)
839 {
840     // Align turret with base
841
842     int turret;           // Turret angle
843     int dtheta;           // Difference between turret and base
844
845     scout_vm(0, 0);
846     sp(DEFAULT_SPEED, FACE_TURN_RATE, 0); // TEMP FIX for SCOUT
847
848     update();
849     turret = State[ 37 ];
850     dtheta = 0;           // fake it for SCOUT
851     // dtheta = wrap(actual_theta - turret, -1800, 1800);
852
853     while(dtheta != 0) {
854         scout_vm(0, 0); // TEMP TECK for SCOUT
855         ws(0, 0, 0, 100);
856
857         update();
858         turret = State[ 37 ];
859         dtheta = wrap(actual_theta - turret, -1800, 1800);
860     }
861 }
862 // END SCOUT THESIS CHANGE

```

```

863     set_default_velocity();
864 }
865
866 void robot::move_rel(int x, int y)
867 {
868     // Relative Cartesian move to <x, y> (world coords, tenths of
869     inches)
870
871     int old_angle;
872     int move_angle;
873     int move_dist;
874
875     update();
876     old_angle = State[ 36] ;
877
878     move_angle = (int) (atan2((double) y, (double) x) * RAD2DEG * 10.0);
879     move_dist = (int) hypot((double) x, (double) y);
880
881     face_angle(move_angle);
882
883     sp(MOVE_TO_SPEED, DEFAULT_TURN_RATE, 0);    // TEMP FIX for SCOUT
884     // BEGIN SCOUT THESIS CHANGE
885
886     // TEMP FIX - change pr to vm and comment out the wait
887     scout_vm(move_dist, 0);
888     // ws(1, 1, 0, 100);    TEMP FIX - comment out the wait
889     // END SCOUT THESIS CHANGE
890     set_default_velocity();
891
892     face_angle(old_angle);
893 }
894
895 void robot::wait_start(void)
896 {
897     // Wait for the robot to start moving (any motor)
898
899     gs();
900
901     while((State[ STATE_VEL_TRANS] == 0) &&
902           (State[ STATE_VEL_STEER] == 0) &&
903           (State[ STATE_VEL_TURRET] == 0)) {
904         gs();
905     }
906 }

```

APPENDIX G. FRONTIER-BASED EXPLORATION CODE – AGENT.H

This appendix contains the header file for the routine that controls the robot's exploration behaviors.

```
1  /*
2
3  agent.h
4
5  Header file for agent class
6
7  */
8
9  #ifndef AGENT_H
10 #define AGENT_H
11
12 #include "drand.h"
13 #include "irand.h"
14 #include "robot.h"
15 #include "place_net.h"
16 #include "arb.h"
17 #include "control_panel.h"
18 #include "bar_graph.h"
19 #include "mobstacle.h"
20 #include "comm++.h"
21 #include "comm.h"
22 #include "frontier.h"
23 #include "path.h"
24
25 // BEGIN SCOUT THESIS CHANGE
26
27 // These are the conversion macros from Nomadic that accept the steering
28 and
29 // translation values as used for the Nomad 150 and 200 and calculate
30 the
31 // differential-drive axis values for the Nomad Scout.
32
33 #define ROTATION_CONSTANT    0.118597 /* inches/degree (known to 100
34 ppm) */
35
36 #define RIGHT(trans, steer)  (trans +
37 (int)((float)steer*ROTATION_CONSTANT))
38 #define LEFT(trans, steer)   (trans -
39 (int)((float)steer*ROTATION_CONSTANT))
40
41 #define scout_vm(trans, steer)  vm(RIGHT(trans, steer), LEFT(trans,
42 steer), 0)
43 #define scout_pr(trans, steer)  pr(RIGHT(trans, steer), LEFT(trans,
44 steer), 0)
45
46 // END SCOUT THESIS CHANGE
47
48
49
50 // Motor control parameters
51
52 const int SPEED_RES = 40;
```

```

53 const double SPEED_MIN = -100.0;
54 const double SPEED_MAX = 100.0;
55 const double SPEED_DEF = 0.0;
56 const double SPEED_NOISE = 5.0;
57
58 const int TURN_RES = 32;
59 const double TURN_MIN = -180.0;
60 const double TURN_MAX = 180.0;
61 const double TURN_DEF = 0.0;
62 const double TURN_NOISE = 5.0;
63
64 // Random turn to escape stasis
65
66 const double RAND_TURN = 10.0;
67
68 // Speed arbitrator window parameters
69
70 const int SPWIN_X = 570;           // x-coord of top
71 const int SPWIN_Y = 460;           // y-coord of left side
72 const int SPWIN_WIDTH = 175;       // Window width
73 const int SPWIN_HEIGHT = 50;        // Window height
74 const double SPWIN_MIN = -20.0;     // Minimum vote total
75 const double SPWIN_MAX = 20.0;      // Maximum vote total
76
77 // Turn arbitrator window parameters
78
79 const int TUWIN_X = 570;           // x-coord of top
80 const int TUWIN_Y = 540;           // y-coord of left side
81 const int TUWIN_WIDTH = 175;       // Window width
82 const int TUWIN_HEIGHT = 50;        // Window height
83 const double TUWIN_MIN = -20.0;     // Minimum vote total
84 const double TUWIN_MAX = 20.0;      // Maximum vote total
85
86 // Power constants
87
88 const double CPU_FULL_VOLTAGE = 12.0;
89 const double CPU_DANGER_VOLTAGE = 11.0;
90
91 const double MOTOR_FULL_VOLTAGE = 12.0;
92 const double MOTOR_DANGER_VOLTAGE = 11.0;
93
94
95 /***** BEHAVIOR CONSTANTS *****/
96
97 // Bump halt
98
99 const int BUMP_SLEEP = 10;          // Number of seconds to sleep
100
101 // Recoil
102
103 const double RECOIL_SPEED = 100.0;
104 const double RECOIL_SPEED_SIGMA = 25.0;
105 const double RECOIL_TURN = 45.0;
106 const double RECOIL_TURN_SIGMA = 10.0;
107 const double RECOIL_WT = 10.0;
108
109 // Maintain alignment
110

```

```

111 const double MAX_BASE_TURRET_DEV = 1.0;
112
113 // Advance
114
115 const int ADV_SLOW_DIST = 60;
116 const int ADV_STOP_DIST = 6;
117 const int ADV_PER_SLOW_DIST = 12;
118 const int ADV_PER_STOP_DIST = 4;
119 const double ADV_SPEED = 75.0;
120 const double ADV_PER_SPEED = 20.0;
121 const double ADV_SPEED_SIGMA = 10.0;
122 const double ADV_SPEED_WT = 5.0;
123
124 // Advance slow
125
126 const int ADV_SLOW_STOP_DIST = 5;
127 const double ADV_SLOW_SPEED = 20.0;
128 const double ADV_SLOW_SPEED_SIGMA = 5.0;
129 const double ADV_SLOW_SPEED_WT = 5.0;
130
131 // Corridor advance
132
133 const int CORRIDOR_SPEED = 25;
134 const int CORRIDOR_SPEED_WIDE = 75;
135
136 // Maintain heading
137
138 const double MH_TURN_SIGMA = 45.0;
139 const double MH_TURN_WT = 1.0;
140
141 // Maintain transit heading
142
143 const double MTH_TURN_SIGMA = 45.0;
144 const double MTH_TURN_WT = 1.0;
145
146 // Avoid
147
148 const int AVOID_DIST = 36;
149 const double AVOID_TURN_SIGMA = 22.5;
150 const double AVOID_WT_FACTOR = 6.0;
151
152 // Transit avoid
153
154 const double TRANSIT_AVOID_TURN_SIGMA = 10.0;
155
156 // Avoid bias
157
158 const int AVOID_BIAS_DIST = 10;
159 const double AVOID_BIAS_ANGLE = 45.0;
160 const double AVOID_BIAS_SIGMA = 45.0;
161 const double AVOID_BIAS_WT = 1.0;
162
163 // Follow wall
164
165 const int FOLLOW_ABORT = 20;
166 const int FOLLOW_MAX_ALIGN_DIST = 40;
167 const int FOLLOW_STOP_DIST = 20;
168 const double FOLLOW_TURN_FACTOR = 0.2;

```



```

169 const double FOLLOW_TURN_SIGMA = 5.0;
170 const double FOLLOW_WT = 2.0;
171
172 // Maintain distance
173
174 const int DESIRED_DIST = 10;
175 const double MD_TURN_FACTOR = 0.2;
176 const double MD_TURN_SIGMA = 3.0;
177 const double MD_WT = 4.0;
178
179 // Follow path
180
181 const double NAV_MIN_ACT = 0.5;
182 const double NAV_SIGMA = 45.0;
183 const double NAV_WT = 5.0;
184
185 // Goal orient
186
187 const double GOAL_SIGMA = 45.0;
188 const double GOAL_WT = 5.0;
189
190 // Goal corridor orient
191
192 const double GOAL_CORRIDOR_NOISE = 5.0;           // Noise in turn angle
193
194 // Center home
195
196 const int CENTER_SPEED = 10;
197 const double CENTER_ERR_THRESH = 0.01;
198
199 // Angle localization
200
201 const int ANGLE_LOC_STEP = 10;
202 const int ANGLE_LOC_NUM_STEPS = 10;
203 const int ANGLE_LOC_SLEEP = 1;
204
205 /***** SEQUENCER CONSTANTS *****/
206
207 // 22.5 degrees between sonars
208
209 const int SONAR_SWEEP_WIDTH = 22;
210
211 // Sonar sweep speed
212
213 const int SONAR_SWEEP_SPEED = 20;
214
215 // Sonar sweep step (degrees)
216
217 const int SONAR_SWEEP_STEP = 2;
218
219 // Sonar sweep pause between steps (microseconds)
220
221 const unsigned int SONAR_SWEEP_PAUSE = 100000;
222
223 // Laser sweep step (degrees)
224
225 const int LASER_SWEEP_STEP = 5;
226

```

```

227 // Laser-limited sonar sweep speed
228
229 const int LLS_TURN_RATE = 150;
230
231 // Identification confirmation sequence (inches)
232
233 const double MAX_CONFIRM_DIST = 1.0;
234
235 // Local navigation sequencer tolerance (inches)
236
237 const double LOCAL_NAV_TOLERANCE = 18.0;
238
239 // Local navigation maximum timesteps for stall
240
241 const int STALL_TIMEOUT = 20;
242
243 // Angle above which local navigation turns robot in place
244
245 const double LOCAL_TIP_ANGLE = 90.0;
246
247 /***** CONTROL INTERFACE PARAMETERS *****/
248
249 const int NUM_CMD = 2; // Number of command outputs
250
251 enum { SPEED, TURN }; // Command indexes
252
253 // Behavior modes
254
255 enum { EXPLORE_MODE, EXPLORE_LLS_MODE, NAVIGATION_MODE, TEST_MODE };
256
257 // Control commands
258
259 enum { CMD_EXPLORE,
260       CMD_NAV, CMD_NAV_KBD, CMD_STOP, CMD_SAVE, CMD_LOAD,
261       CMD_REDRAW, CMD_BUILD_GRID, CMD_SAVE_GRID, CMD_LOAD_GRID,
262       CMD_GRID_IDENT, CMD_GRID, CMD_CLEAR, CMD_CLEAR_ROBOT,
263       CMD_SONAR_SCAN, CMD_SONAR_SWEEP, CMD_SONAR_SWEEP_ABS,
264       CMD_CLEAR_SONAR,
265       CMD_LASER_SCAN, CMD_LASER_SWEEP, CMD_LASER_SWEEP_ABS,
266       CMD_CLEAR_LASER,
267       CMD_LLS_SCAN, CMD_LLS_SWEEP, CMD_LLS_SWEEP_ABS, CMD_CLEAR_LLS,
268       CMD_GRID_UNDO, CMD_CENTER, CMD_PLACE_MAP,
269       CMD_PLACE_IDENT, CMD_PLACE_GRID,
270       CMD_LOCAL_NAV, CMD_ADD_PLACE, CMD_EDIT_PLACE,
271       CMD_ADD_EDIT_LINK, CMD_DELETE_LINK,
272       CMD_CLEAR_GLOBAL, CMD_SAVE_GLOBAL, CMD_LOAD_GLOBAL,
273       CMD_DISPLAY_GLOBAL, CMD_GLOBAL_UNDO, CMD_INTEGRATE_GRID,
274       CMD_FIND_FRONTIERS, CMD_DISPLAY_EDGES, CMD_DISPLAY_FRONTIERS,
275       CMD_GOTO_FRONTIER, CMD_UPDATE_NAV_GRID, CMD_DETECT_CORRIDORS,
276       CMD_CONNECT_CL, CMD_SEND_CL_GRID,
277       CMD_BUMP,
278       CMD_INIT_COMM, CMD_SEND_MSG, CMD_RECEIVE_MSG,
279       CMD_EXIT };
280
281 /***** GRAPHICS CONSTANTS *****/
282
283 // Control window graphic parameters
284

```

```

285 const int CON_NUM_CMD = CMD_EXIT + 1;      // Number of command buttons
286
287 const int CON_WIN_LEFT = 850;              // x-coord of left side
288 const int CON_WIN_TOP = 0;                 // x-coord of top
289
290 // Number of button columns
291 const int CON_COLS = 2;
292
293 // Number of button rows
294 const int CON_ROWS = (int) ((double) CON_NUM_CMD / 2.0 + 0.5);
295
296 const int CON_BUTTON_WIDTH = 150;          // Button width
297 const int CON_BUTTON_HEIGHT = 25;          // Button height
298
299 const int CON_LAB_WIDTH = 130;              // Label width
300                                         // (Must be less than button width)
301 const int CON_LAB_HEIGHT = 10;             // Label height
302                                         // (Must be less than button height)
303
304 // Evidence grid window screen boundaries
305
306 const int EGWIN_LEFT = 420;
307 const int EGWIN_TOP = 0;
308 const int EGWIN_RIGHT = 932;
309 const int EGWIN_BOTTOM = 512;
310
311 // Evidence grid window world coordinate boundaries
312
313 const int EGWIN_WC_LEFT = -3000;
314 const int EGWIN_WC_BOTTOM = -3000;
315 const int EGWIN_WC_RIGHT = 3000;
316 const int EGWIN_WC_TOP = 3000;
317
318 // Navigation grid window screen boundaries
319
320 const int NAV_WIN_LEFT = 420;
321 const int NAV_WIN_TOP = 0;
322 const int NAV_WIN_RIGHT = 932;
323 const int NAV_WIN_BOTTOM = 512;
324
325 // Navigation grid window world coordinate boundaries
326
327 const int NAV_WIN_WC_LEFT = -6000;
328 const int NAV_WIN_WC_BOTTOM = -6000;
329 const int NAV_WIN_WC_RIGHT = 6000;
330 const int NAV_WIN_WC_TOP = 6000;
331
332 /*
333 const int NAV_WIN_WC_LEFT = -3000;
334 const int NAV_WIN_WC_BOTTOM = -3000;
335 const int NAV_WIN_WC_RIGHT = 3000;
336 const int NAV_WIN_WC_TOP = 3000;
337 */
338
339 // Global evidence grid window screen boundaries
340
341 const int GLOBAL_WIN_LEFT = 0;
342 const int GLOBAL_WIN_TOP = 0;

```

```

343 const int GLOBAL_WIN_RIGHT = 1024;
344 const int GLOBAL_WIN_BOTTOM = 1024;
345
346 /*
347 const int GLOBAL_WIN_LEFT = 0;
348 const int GLOBAL_WIN_TOP = 0;
349 const int GLOBAL_WIN_RIGHT = 512;
350 const int GLOBAL_WIN_BOTTOM = 512;
351 */
352
353 // Evidence grid window world coordinate boundaries
354
355 const int GLOBAL_WIN_WC_LEFT = -6000;
356 const int GLOBAL_WIN_WC_BOTTOM = -6000;
357 const int GLOBAL_WIN_WC_RIGHT = 6000;
358 const int GLOBAL_WIN_WC_TOP = 6000;
359
360 /*
361 const int GLOBAL_WIN_WC_LEFT = -3000;
362 const int GLOBAL_WIN_WC_BOTTOM = -3000;
363 const int GLOBAL_WIN_WC_RIGHT = 3000;
364 const int GLOBAL_WIN_WC_TOP = 3000;
365 */
366
367 // Color of robot in global window
368
369 static char GLOBAL_ROBOT_COLOR[ STRLEN] = "Blue";
370
371 // Color of contact marker in global window
372
373 static char CONTACT_COLOR[ STRLEN] = "Red";
374
375 // Size of contact marker in global window
376
377 const int CONTACT_MARK_SIZE = 50;
378
379 /***** FRONTIER CONSTANTS *****/
380
381 // Maximum number of frontiers
382
383 const int MAX_FRONTIERS = 1000;
384
385 // Radius of neighborhood around visited frontier (1/10 inch)
386
387 const double VISIT_RADIUS = 60.0;
388
389 // Radius of neighborhood around inaccessible frontier (1/10 inch)
390
391 const double INAC_RADIUS = 120.0;
392
393 // Maximum number of colors for blob coloring
394
395 const int MAX_COLORS = 1000;
396
397 // Number of colors to display
398
399 const int DISPLAY_COLORS = 16;
400

```

```

401 // Radius of region centroid marker
402
403 const double CENTROID_MARK_RADIUS = 75.0;
404
405 // Minimum region size
406
407 const int MIN_REGION_SIZE = 6;
408 // const int MIN_REGION_SIZE = 1;
409
410 // Maximum frontier distance
411
412 const double MAX_DIST = 100000.0;
413
414 // Frontier edge color
415
416 static char EDGE_COLOR[ STRLEN] = "red";
417
418 // Color table
419
420 static char color_table[ DISPLAY_COLORS][ STRLEN] = {
421     "Blue", "Green", "Gold", "Red",
422     "SkyBlue", "LimeGreen", "Orange", "Magenta",
423     "RoyalBlue", "Cyan", "LightCoral", "Violet",
424     "SteelBlue", "Aquamarine", "Purple", "Turquoise" };
425
426 // Color conversions for robot window
427
428 static int robot_color[ DISPLAY_COLORS] = {
429     1, 6, 11, 16,
430     2, 7, 12, 17,
431     3, 8, 13, 18,
432     4, 9, 15, 20 };
433
434 /***** NAVIGATION CONSTANTS *****/
435
436 // Distance to retreat on bumper contact (1/10 inch)
437
438 const int BUMP_RECOIL = 20;
439
440 // Speed of bump recoil
441
442 const int BUMP_RECOIL_SPEED = 20;
443
444 // Search status codes
445
446 const int SEARCH_SUCCESS = 0;
447 const int SEARCH_FAIL = 1;
448 const int SEARCH_TIMEOUT = 2;
449
450 // Maximum number of cells to search
451
452 const int SEARCH_MAX_CELLS = 10000;
453
454 // Maximum number of obstacle cells allowed in path region
455
456 const int MAX_OBS_COUNT = 2;
457
458 // Color of path in grid/global window

```



```

459
460 static char PATH_COLOR[ STRLEN] = "Red";
461 static char OPT_PATH_COLOR[ STRLEN] = "Blue";
462 static char TRAV_PATH_COLOR[ STRLEN] = "Red";
463
464 // Color of path in robot window
465
466 const int ROBOT_PATH_COLOR = 16;      // Red
467 const int ROBOT_OPT_PATH_COLOR = 2;    // Blue
468 const int ROBOT_TRAV_PATH_COLOR = 16;  // Red
469
470 // Waypoint lookahead window (# waypoints)
471
472 const int WAYPOINT_WINDOW = 5;
473
474 // Number of waypoints between LLS sweeps during navigation
475
476 const int NAV_LLS_SWEEP_INTERVAL = 10000; // Never
477
478 /***** CORRIDOR CONSTANTS *****/
479
480 // Number of sensors to either side of sensor to check
481
482 const int CORRIDOR_SPAN = 3;
483
484 // Amount of forward space needed to be clear
485
486 const int CORRIDOR_FWD_RANGE = 12;
487
488 // Amount of space needed on sides of robot
489
490 const int CORRIDOR_SIDE_CLEARANCE = 6;
491
492 // Amount of forward space for wide corridor
493
494 const int CORRIDOR_WIDE_FWD_RANGE = 48;
495
496 // Amount of side space for a wide corridor
497
498 const int CORRIDOR_WIDE_SIDE_CLEARANCE = 24;
499
500 // Maximum deviation between corridor angle and goal bearing
501
502 const double CORRIDOR_MAX_DEVIATION = 90.0;
503
504 // Color of corridor in global window
505
506 static char CORRIDOR_COLOR[ STRLEN] = "Blue";
507 static char CORRIDOR_WIDE_COLOR[ STRLEN] = "Green";
508 static char CORRIDOR_SELECT_COLOR[ STRLEN] = "Red";
509 static char CORRIDOR_SELECT_WIDE_COLOR[ STRLEN] = "Gold";
510
511 // Color of corridor in robot window
512
513 const int CORRIDOR_COLOR_ROBOT = 2;      // Blue
514 const int CORRIDOR_WIDE_COLOR_ROBOT = 6;  // Green
515 const int CORRIDOR_SELECT_COLOR_ROBOT = 14; // DeepPink
516 const int CORRIDOR_SELECT_WIDE_COLOR_ROBOT = 11; // Yellow

```

```

517
518 /***** CONTINUOUS LOCALIZATION DECLARATIONS *****/
519
520 // Continuous localization host
521
522 static char CONTLOC_HOST[ STRLEN] = "sun28";
523
524 // Continuous localization communication channel ID
525
526 const int CONTLOC_CHANNEL = 0;
527
528 // Minimum number of occupied cells for usable map
529
530 const int CONTLOC_MIN_OCC = 0;
531
532 // Exploration relocation interval (inches)
533
534 const int EXPLORE_RELOC_DISTANCE = 96;
535
536 // Navigation relocation interval (inches)
537
538 const int NAV_RELOC_DISTANCE = 24;
539
540 /***** MULTIROBOT DECLARATIONS *****/
541
542 // Message indicating new map exists
543
544 static char NEW_MAP_MSG[ STRLEN] = "NEWMAP";
545
546 /***** MISCELLANEOUS DECLARATIONS *****/
547
548 // Status codes
549
550 const int OK = 0;
551 const int ALT = 1;
552 const int RETRY = 2;
553 const int ABORT = -1000;
554 const int TIMEOUT = -1001;
555 const int NO_PATH = -1002;
556 const int NO_FRONTIERS = -1003;
557
558 // External C functions
559
560 extern "C" int abs(int);
561 extern "C" int sleep(int);
562 extern "C" int usleep(unsigned int);
563 extern "C" void exit(int);
564 extern "C" void registergrids(Map3D map1, Map3D map2, double *dx,
565                             double *dy, double *dt, double *fitness);
566
567 // Number of moving obstacles
568
569 const int NUM_MOB = 0;
570
571 // Length of experimental trial (steps)
572
573 //const int TRIAL_LENGTH = 10000;
574

```

```

575 const int TRIAL_LENGTH = 50000;
576
577 //const int TRIAL_LENGTH = 1000000000;    // Run forever
578
579 // Margin for random robot placement
580
581 const int RAND_MARGIN = 200;
582
583 class agent {
584
585 public:
586     agent(void);                // Constructor
587     void control(void);         // Main control loop
588
589 private:
590     int bumped[ NUM_TOUCH] ;    // BUMPER HACK ARRAY
591
592     robot r;                    // Controlled robot
593     arbitrator *speed_arb;      // Speed command arbitrator
594     arbitrator *turn_arb;       // Turn command arbitrator
595     place_net pnet;            // Place network
596     char apndir[ STRLEN] ;      // Name of APN directory
597
598     mobstacle mob_list[ NUM_MOB + 1] ; // Moving obstacles
599
600     Map3D global_grid;          // Global evidence grid
601     Map3D old_global;           // Old global evidence grid
602     Map3D egrid;               // Evidence grid
603     Map3D old_grid;            // Old evidence grid
604     Map3D edge_grid;           // Frontier edge grid
605     Map3D nav_grid;            // Navigation grid
606
607     int region_map[ GLOBAL_X_RES][ GLOBAL_Y_RES] ; // Colored region grid
608
609     int visit[ NAV_X_RES][ NAV_Y_RES] ; // Visit map for path planning
610
611     frontier frontiers[ MAX_FRONTIERS] ; // List of frontiers
612     int num_front;              // Number of frontiers
613
614     frontier front_visit[ MAX_FRONTIERS] ; // Visited frontiers
615     int num_visit;             // Number of visited frontiers
616
617     frontier front_inac[ MAX_FRONTIERS] ; // Inaccessible frontiers
618     int num_inac;              // Number of inaccessible frontiers
619
620     int corridor[ NUM_RANGE] ; // Corridor detection array
621     int wide_corridor[ NUM_RANGE] ; // Wide corridor detection
622     array
623
624     CylSensorModelArray sonar_smd; // Sonar sensor model
625     CylSensorModelArray sonar_clear_smd; // Sonar sensor model (clear)
626
627     control_panel control_window; // Control window
628     // bar_graph speed_window; // Speed command display
629     // bar_graph turn_window; // Turn command display
630     window *grid_window; // Evidence grid window (pointer)
631     // window *nav_window; // Navigation grid window (pointer)
632     window *global_window; // Global grid window (pointer)

```

```

633
634     int global_refresh;           // Set when global grid is displayed
635     int realtime_display;        // Flags whether to display robot
636
637     ofstream *logfile;           // Log file
638
639     int multi_mode;               // Multirobot mode (0:single, 1:multi)
640     int contloc_mode;            // Continuous localization mode
641     int behavior_mode;           // Behavior mode
642     int home_dist;               // Path distance from home
643
644     int destin;                  // Destination index
645
646     int timer;                   // Total elapsed time (steps)
647
648     double cpu_volt;              // CPU battery voltage
649     double motor_volt;           // Motor battery voltage
650     double cpu_min;              // Minimum CPU battery voltage
651     double motor_min;            // Minimum motor battery voltage
652
653     double transit_dir;          // Transit direction
654
655     int pause_mode;
656
657     int cell_count;              // Number of cells searched
658
659     void reset(void);            // Reset position and timer
660     int user_command(void);      // Execute user command (if any)
661     int iscan(void);             // Scan for interrupt
662     void terminate(void);        // End session
663     void power_check(void);      // Check battery power
664
665     // Behavior modes
666
667     void bump_test(void);        // Bumper test
668     void manual_exploration(void); // Map territory under manual
669 control
670     void exploration(void);       // Explore uncharted territory
671     void exploration_lls(void);   // Explore uncharted territory (LLS)
672     void reactive_exploration(void); // Explore uncharted territory
673     // reactively
674     void navigation(void);        // Navigate to destination (mouse)
675     void navigation_keyboard(void); // Navigate to destination
676 (keyboard)
677     void local_navigation(void);  // Navigate to local
678 destination point
679     void frontier_navigate(void); // Navigate to frontier
680 centroid
681
682     // Explore uncharted territory (multiple trials)
683     void multi_exploration(void);
684
685     // Explore uncharted territory reactively (multiple trials)
686     void multi_reactive_exploration(void);
687
688     // Behavior sequencers
689
690     // Manual exploration sequencer

```

```

691 void manual_exploration_seq(void);
692
693 // Exploration sequencer
694 void exploration_seq(void);
695
696 // Exploration sequencer (laser-limited sonar)
697 void exploration_lls_seq(void);
698
699 // Reactive exploration sequencer
700 void reactive_exploration_seq(void);
701
702 int navigation_seq(void);           // Navigation sequencer
703 void search_seq(void);             // Search sequencer
704 void map_seq(void);                // Build local grid
705 void center_seq(void);             // Move to center of current place
706
707 // Local navigation sequencer
708 int local_nav_seq(int x, int y);    // Local destination coordinates
709
710 // Local navigation sequencer for path following
711 int path_local_nav_seq(path p,      // Path to follow
712                        int &waypoint); // Index of next waypoint
713
714 // Local navigation sequencer (continuous motion)
715 int local_cont_nav_seq(int x, int y); // Local destination coords
716
717 // Local navigation sequencer (with alternate goal)
718 int local_nav_seq_alt(int gx, int gy, // Goal coordinates
719                      int ax, int ay); // Alternate goal coordinates
720
721 // Navigate to goal by planning and following path
722 int path_nav_seq(double gx, double gy); // World coords of goal
723
724 // Navigate to frontier by planning and following path
725 int frontier_path_nav_seq(int front_index); // Frontier index
726
727 // Place identification sequencer
728 void ident_seq(void);
729
730 // Grid identification sequencer
731 void grid_ident_seq(void);
732
733 // Rotate and reset DR angle to match stored range image
734 void angle_loc_seq(int image[ NUM_RANGE] );
735
736 // Translate to match stored range image
737 void trans_loc_seq(int image[ NUM_RANGE] );
738
739 // Rotate sonar sensors and scan
740 void sonar_sweep_seq(Map3D map);
741
742 // Rotate sonar sensors and scan (absolute coordinates)
743 void sonar_sweep_abs_seq(Map3D map);
744
745 // Rotate laser scanner and scan
746 void laser_sweep_seq(Map3D map);
747
748 // Rotate laser scanner and scan (absolute coordinates)

```



```

749 void laser_sweep_abs_seq(Map3D map);
750
751 // Laser-limited sonar sweep
752 void lls_sweep_seq(Map3D map);
753
754 // Laser-limited sonar sweep (absolute coordinates)
755 void lls_sweep_abs_seq(Map3D map);
756
757 // Navigate to selected frontier
758 int frontier_nav_seq(int front_index); // Frontier destination index
759
760 // Behavior sets
761
762 // Behavior set for reactive exploration
763 int reactive_explore_behaviors(void);
764
765 int navigation_behaviors(void); // Behavior set for navigation
766
767 // Behavior set for local navigation
768 int local_navigation_behaviors(int gx, int gy);
769
770 // Behaviors
771
772 /***** LOW-LEVEL BEHAVIORS *****/
773
774 void bump_halt(void); // Go limp if bumper touched
775 void recoil(void); // If touched in forward half, move
776 backward
777 void bump_recoil(void); // If bumper contact, recoil away
778 void wander(void); // Make small random turns
779 int advance(void); // Move forward unless front is blocked
780 int advance_slow(void); // Move forward slowly unless front is
781 blocked
782
783 // Realign turret if it is not aligned with base
784 void maintain_alignment(void);
785
786 // Avoid nearby obstacles
787 void avoid(void);
788
789 // If front is completely blocked, bias avoidance toward the left side
790 void avoid_bias_left(void);
791
792 // If front is completely blocked, bias avoidance toward the right
793 side
794 void avoid_bias_right(void);
795
796 // Maintain current heading
797 void maintain_heading(void);
798
799 void veer(void); // Veer away from potential collisions.
800
801 void follow_wall_right(void); // Align with right wall
802 void follow_wall_left(void); // Align with left wall
803
804 // Maintain desired distance from right wall
805 void maintain_distance_right(void);
806

```

```

807 // Maintain desired distance from left wall
808 void maintain_distance_left(void);
809
810 // Turn toward goal
811 void goal_orient(int gx, int gy);
812
813 /***** NAVIGATION BEHAVIORS *****/
814
815 int follow_path(void);           // Turn to follow path
816 int detect_dest(int destin);     // Detect arrival at
817 destination
818
819 // Low-level commands
820
821 void set_defaults(void);         // Set default command values
822 void update(void);              // Update robot state and evidence grid
823 void execute(void);             // Send commands to robot
824
825 // Move obstacles
826 void move_obstacles(void);
827
828 // Delete obstacles
829 void del_obstacles(void);
830
831 // File access commands
832
833 void save_net(void);            // Save network in file
834 void load_net(void);           // Load network from file
835
836 /***** LOCALIZATION FUNCTIONS *****/
837
838 // Compute difference between image and range input
839 double compute_range_err(int image[ NUM_RANGE], vector rinput);
840
841 // Compute translation vector between expected and actual position
842 void trans_loc_vector(int image[ NUM_RANGE], int &dx, int &dy);
843
844 /***** EVIDENCE GRID FUNCTIONS *****/
845
846 // Display evidence grid in X window
847 void grid_display(window *win,    // Window pointer
848                  Map3D map);      // Evidence grid
849
850 // Display global evidence grid in X window
851 void grid_display_global(Map3D map); // Evidence grid
852
853 // Display local grid for place
854 void display_place_grid(void);
855
856 // Display edge segments detected in evidence grid
857 void grid_display_edges(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] );
858
859 // Display regions detected in evidence grid
860 void grid_display_regions(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] );
861
862 // Display robot in window
863 void display_robot(window *win,    // Window
864                  int x, int y,    // Robot position (1/10 inch)

```

```

865             int theta,           // Robot heading (1/10 degree)
866             int turret); // Robot turret angle (1/10 degree)
867
868 /***** FRONTIER FUNCTIONS *****/
869
870 // Copy frontier <f2> to frontier <f1>
871 void frontier_copy(frontier &f1, frontier f2);
872
873 // Find frontiers in global grid
874 void find_frontiers(void);
875
876 // Find frontier edges in <raw> grid and store them in <edge> grid
877 void find_frontier_edges(Map3D *raw,           // Raw evidence grid
878 (pointer)
879             Map3D *edge,           // Frontier edge grid
880 (pointer)
881             double height);        // Z-axis of edge plane
882
883 // Find frontier regions in <edge> grid and add new frontiers
884 void find_frontier_regions(Map3D edge, // Frontier edge grid
885             double height);          // Z-coord of edge plane
886
887
888 // Segment <grid> image into regions in <color> using spreading
889 activation
890 void spread_segment(Map3D grid,           // Uncolored grid
891             int color[ GLOBAL_X_RES][ GLOBAL_Y_RES], // Colored grid
892             double height);              // Z-coord of edge plane
893
894 // Print colored grid cell values
895 void print_region_map(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] ); //
896 Colored grid
897
898 // Determine size and centroid of frontier regions
899 void analyze_regions(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] ); //
900 Colored grid
901
902 // Check whether centroid corresponds to previously visited frontier
903 // Return 1 if visited, 0 otherwise
904 int agent::visited(double cx, double cy);
905             // Centroid of new region
906
907 // Check whether centroid corresponds to inaccessible frontier
908 // Return 1 if inaccessible, 0 otherwise
909 int agent::inaccessible(double cx, double cy);
910             // Centroid of new region
911
912 // Return index of unvisited, accessible frontier closest to (x, y)
913 // Return -1 if no such frontier exists
914 int closest_frontier(double x, double y);
915
916 // Mark region centroids in evidence grid window
917 void display_region_centroids(double cx,           // Display center x-
918 coord
919             double cy); // Display center y-coord
920
921 // Mark region centroids in robot window
922 void display_robot_region_centroids(void);

```

```

923
924 // Check whether cell (x, y) is part of frontier <front_index>
925 int check_frontier_cell(int x, int y, // Cell index
926                        int front_index); // Frontier index
927
928
929 /***** NAVIGATION FUNCTIONS *****/
930
931 // Move forward if front corridor is clear
932 void corridor_advance(void);
933
934 // Turn toward clear corridor closest to goal bearing
935 void goal_corridor_orient(int gx, int gy);
936
937 // Update navigation grid based on global grid
938 void update_nav_grid(void);
939
940 // Plan path to goal location (return 1 if path found, 0 otherwise)
941 int path_plan(double wx, double wy, // World coords of goal
942              path &nav_path); // Navigation path (optimized)
943
944 // Plan path to goal location (return 1 if path found, 0 otherwise)
945 int frontier_path_plan(double wx, double wy, // World coords of goal
946                      int front_index, // Frontier index
947                      path &nav_path); // Navigation path
948
949 // Print all cells on path
950 void print_path(path p);
951
952 // Draw path in window
953 void display_path(path p, // Path
954                  char *pcolor, // Path color
955                  window *win); // Window
956
957 // Draw path in robot window
958 void display_path_robot(path p, // Path
959                       int pcolor); // Path color
960
961 // Find path from (sx, sy) to (gx, gy)
962 int find_path(int sx, int sy, // Start cell
963              int gx, int gy, // Goal cell
964              path &p); // Path
965
966 // Find path from (sx, sy) to (gx, gy) or any point on frontier
967 <front_index>
968 int frontier_find_path(int sx, int sy, // Start cell
969                      int gx, int gy, // Goal cell
970                      int front_index, // Frontier index
971                      path &p); // Path
972
973 // Search cell (x,y) and return search status
974 int search_cell(int x, int y, // Search cell
975                int gx, int gy, // Goal cell
976                path &p); // Path
977
978 // Search cell (x,y) while navigating to frontier and return search
979 status
980 int frontier_search_cell(int x, int y, // Search cell

```

```

981             int gx, int gy,                // Goal cell
982             int front_index,                // Frontier index
983             path &p);                        // Path
984
985 // Find index of (unvisited) neighbor closest to goal
986 int closest_neighbor(int x, int y,          // Current cell index
987                     int gx, int gy,        // Goal cell index
988                     int &nx, int &ny);      // Next cell index
989
990 // Reverse order of steps on path
991 void reverse_path(path old_path,            // Initial path
992                  path &new_path);          // Reversed path
993
994
995 // Optimize path by jumping between adjacent path cells
996 void optimize_path(path old_path, // Initial path
997                   path &new_path); // Optimized path
998
999 // Convert path in grid cell coords to world coords
1000 void generate_world_path(path grid_path,    // Path in nav grid
1001                          path &world_path); // Path in world coords
1002
1003 // Initialize path
1004 void path_init(path &p);    // Path
1005
1006 // Add point to path
1007 void path_add(path &p,      // Path
1008              int x, int y); // Point to add to path
1009
1010 // Check to see whether region around point is free of known
1011 obstacles
1012 int check_clear(int x, int y);
1013
1014 // Check to see whether region around point overlaps frontier
1015 int check_frontier_arrival(int x, int y, int front_index);
1016
1017 // Finds waypoint furthest on path within destination tolerance, or
1018 // waypoint on path <p> closest to (x, y), returning the distance
1019 // to that point, and the waypoint's index in <index>
1020 double closest_waypoint(path p,          // Path
1021                        int x, int y,     // Current position (1/10
1022 inch)
1023                        int index,        // Index of current waypoint
1024                        int &close_index); // Index of closest waypoint
1025
1026 /***** CORRIDOR FUNCTIONS *****/
1027
1028 // Detect freespace corridors in vicinity of robot
1029 void detect_corridors(void);
1030
1031 // Check whether a corridor exists centered around sensor <center>
1032 // Return 1 if true, 0 otherwise
1033 int check_corridor(int center,          // Index of sensor in center of
1034 corridor
1035                  int fwd_range,        // Required forward space
1036                  int side_clear);      // Required side space
1037
1038

```



```

1039 // Check whether <sensor> is clear for corridor <center>
1040 int corridor_check_sensor(int center,          // Center sensor index
1041                          int sensor,          // Sensor index
1042                          int fwd_range,       // Required fwd space
1043                          int side_clear);     // Required side space
1044
1045 // Display corridors in robot window
1046 void display_corridors(void);
1047
1048 // Display corridor boundaries centered around sensor <center>
1049 void display_corridor(window *win,            // Window
1050                      int center, // Center sensor index
1051                      int fwd_range, // Required forward space
1052                      int side_clear, // Required side space
1053                      char *color); // Corridor color
1054
1055 // Display corridor boundaries centered around sensor <center> in
1056 robot window
1057 void display_corridor_robot(int center, // Center sensor index
1058                            int fwd_range, // Required forward space
1059                            int side_clear, // Required side space
1060                            int color); // Corridor color
1061
1062 // Select corridor nearest to specified heading
1063 int select_corridor(double heading); // Heading (degrees)
1064
1065 /***** INTERFACE TO CONTINUOUS LOCALIZATION *****/
1066
1067 // Initialize communications with continuous localization
1068 void connect_cl(void);
1069
1070 // Send global grid to continuous localization
1071 void send_cl_grid(void);
1072
1073 /***** MULTIROBOT COMMUNICATION *****/
1074
1075 // Initialize robot communication channel
1076 void init_robot_comm(void);
1077
1078 // Send message to other robot
1079 void send_robot_message(char *message);
1080
1081 // Send message to other robot (user mode)
1082 void user_send_robot_message(void);
1083
1084 // BEGIN SCOUT THESIS CHANGE
1085
1086 // Receive message from other robot
1087 // Returns 1 if message received, 0 otherwise
1088 int receive_robot_message(int channel, char *message);
1089
1090 // END SCOUT THESIS CHANGE
1091
1092 // Receive message from other robot (user mode)
1093 void user_receive_robot_message(void);
1094
1095 /***** MULTIROBOT EXPLORATION *****/
1096

```

```
1097     // Integrate new map from remote robot (if a new map exists)
1098     void integrate_remote_map(void);
1099 };
1100
1101 #endif
```

APPENDIX H. FRONTIER-BASED EXPLORATION CODE – AGENT.CC

This appendix contains the source code for the routine that controls the robot's exploration behaviors.

```
1  /*
2
3      agent.cc
4
5      Agent class
6      Original code by Brian Yamauchi
7
8      Modifications for SCOUT THESIS
9      By Patrick A. Hillmeyer
10
11  */
12
13  #include <iostream.h>
14  #include <math.h>
15  #include <string.h>
16
17  #include "agent.h"
18
19  // Arc direction strings
20
21  const char dir_str[16][20] =
22  { "forward", "fwd-fwd-lf", "fwd-lf", "fwd-lf-lf",
23    "left", "back-lf-lf", "back-lf", "back-back-lf",
24    "back", "back-back-rt", "back-rt", "back-rt-rt",
25    "right", "fwd-rt-rt", "fwd-rt", "fwd-fwd-rt" };
26
27  const char voice_str[16][STRLEN] =
28  { "forward 0.", "forward 1.", "forward left 2.", "left 3.",
29    "left 4.", "left 5.", "back left 6.", "back 7.",
30    "back 8 .", "back 9.", "back right 10.", "right 11.",
31    "right 12.", "right 13.", "forward right 14.", "forward 15." };
32
33  /***** AGENT CLASS CONSTRUCTOR *****/
34
35  agent::agent(void)
36  {
37
38      char Global_Grid[STRLEN];          // Global Grid label
39      char Control_Panel[STRLEN];        // Control Panel Label
40
41      // Constructor
42
43      char labels[MAX_CON][CON_LEN];
44      int i;
45
46      // Initialize mode flags
47
48      multi_mode = 0;
49      behavior_mode = EXPLORE_MODE;
50      contloc_mode = 0;
51      home_dist = 0;
52      destin = 0;
```

```

53
54 // Initialize graphics flags
55
56 global_refresh = 1;
57 realtime_display = 1;
58
59 // Initialize frontier counters
60
61 num_front = 0;
62 num_inac = 0;
63
64 // Initialize power variables
65
66 cpu_volt = CPU_FULL_VOLTAGE;
67 motor_volt = MOTOR_FULL_VOLTAGE;
68
69 cpu_min = cpu_volt;
70 motor_min = motor_volt;
71
72 // Initialize abitrator windows
73
74 speed_arb = new arbitrator(SPEED_RES, SPEED_MIN, SPEED_MAX,
75 SPEED_DEF, 0,
76 SPEED_NOISE);
77 if (speed_arb == NULL) {
78     cout << "agent::agent: Unable to allocate space for speed
79 arbitrator."
80         << endl;
81     exit(-1);
82 }
83
84 turn_arb = new arbitrator(TURN_RES, TURN_MIN, TURN_MAX, TURN_DEF, 1,
85 TURN_NOISE);
86 if (turn_arb == NULL) {
87     cout << "agent::agent: Unable to allocate space for turn
88 arbitrator."
89         << endl;
90     exit(-1);
91 }
92
93 // speed_window.init(SPWIN_X, SPWIN_Y, SPWIN_WIDTH, SPWIN_HEIGHT,
94 "Speed",
95 // SPEED_RES, SPWIN_MIN, SPWIN_MAX);
96 // turn_window.init(TUWIN_X, TUWIN_Y, TUWIN_WIDTH, TUWIN_HEIGHT,
97 "Turn",
98 // TURN_RES, TUWIN_MIN, TUWIN_MAX);
99
100 // Initialize control window
101
102 strcpy(labels[ CMD_EXPLORE ], "EXPLORE");
103 strcpy(labels[ CMD_NAV ], "NAVIGATE");
104 strcpy(labels[ CMD_NAV_KBD ], "NAVIGATE (KBD)");
105 strcpy(labels[ CMD_STOP ], "STOP");
106 strcpy(labels[ CMD_SAVE ], "SAVE APN");
107 strcpy(labels[ CMD_LOAD ], "LOAD APN");
108 strcpy(labels[ CMD_REDRAW ], "DISPLAY APN");
109 strcpy(labels[ CMD_BUILD_GRID ], "BUILD GRID");
110 strcpy(labels[ CMD_SAVE_GRID ], "SAVE GRID");

```

```

111 strcpy(labels[ CMD_LOAD_GRID], "LOAD GRID");
112 strcpy(labels[ CMD_GRID], "DISPLAY GRID");
113 strcpy(labels[ CMD_CLEAR], "CLEAR GRID");
114 strcpy(labels[ CMD_CLEAR_ROBOT], "CLEAR ROBOT (ABS)");
115 strcpy(labels[ CMD_SONAR_SCAN], "SONAR SCAN");
116 strcpy(labels[ CMD_SONAR_SWEEP], "SONAR SWEEP");
117 strcpy(labels[ CMD_SONAR_SWEEP_ABS], "SONAR SWEEP (ABS)");
118 strcpy(labels[ CMD_CLEAR_SONAR], "CLEAR + SONAR SWEEP");
119 strcpy(labels[ CMD_LASER_SCAN], "LASER SCAN");
120 strcpy(labels[ CMD_LASER_SWEEP], "LASER SWEEP");
121 strcpy(labels[ CMD_LASER_SWEEP_ABS], "LASER SWEEP (ABS)");
122 strcpy(labels[ CMD_CLEAR_LASER], "CLEAR + LASER SWEEP");
123 strcpy(labels[ CMD_LLS_SCAN], "LLS SCAN");
124 strcpy(labels[ CMD_LLS_SWEEP], "LLS SWEEP");
125 strcpy(labels[ CMD_LLS_SWEEP_ABS], "LLS SWEEP (ABS)");
126 strcpy(labels[ CMD_CLEAR_LLS], "CLEAR + LLS SWEEP");
127 strcpy(labels[ CMD_GRID_UNDO], "UNDO SCAN/SWEEP");
128 strcpy(labels[ CMD_GRID_IDENT], "GRID IDENT");
129 strcpy(labels[ CMD_CENTER], "PLACE CENTER");
130 strcpy(labels[ CMD_PLACE_MAP], "PLACE MAP");
131 strcpy(labels[ CMD_PLACE_IDENT], "PLACE IDENT");
132 strcpy(labels[ CMD_PLACE_GRID], "DISPLAY PLACE GRID");
133 strcpy(labels[ CMD_LOCAL_NAV], "LOCAL NAVIGATION");
134 strcpy(labels[ CMD_ADD_PLACE], "ADD PLACE");
135 strcpy(labels[ CMD_EDIT_PLACE], "EDIT PLACE");
136 strcpy(labels[ CMD_ADD_EDIT_LINK], "ADD/EDIT LINK");
137 strcpy(labels[ CMD_DELETE_LINK], "DELETE LINK");
138 strcpy(labels[ CMD_CLEAR_GLOBAL], "CLEAR GLOBAL GRID");
139 strcpy(labels[ CMD_SAVE_GLOBAL], "SAVE GLOBAL GRID");
140 strcpy(labels[ CMD_LOAD_GLOBAL], "LOAD GLOBAL GRID");
141 strcpy(labels[ CMD_DISPLAY_GLOBAL], "DISPLAY GLOBAL GRID");
142 strcpy(labels[ CMD_GLOBAL_UNDO], "UNDO GLOBAL CHANGES");
143 strcpy(labels[ CMD_INTEGRATE_GRID], "INTEGRATE LOCAL GRID");
144 strcpy(labels[ CMD_FIND_FRONTIERS], "FIND FRONTIERS");
145 strcpy(labels[ CMD_DISPLAY_EDGES], "DISPLAY EDGES");
146 strcpy(labels[ CMD_DISPLAY_FRONTIERS], "DISPLAY FRONTIERS");
147 strcpy(labels[ CMD_GOTO_FRONTIER], "GO TO FRONTIER");
148 strcpy(labels[ CMD_UPDATE_NAV_GRID], "UPDATE NAV GRID");
149 strcpy(labels[ CMD_DETECT_CORRIDORS], "DETECT CORRIDORS");
150 strcpy(labels[ CMD_CONNECT_CL], "CONNECT TO CONTLOC");
151 strcpy(labels[ CMD_SEND_CL_GRID], "SEND CONTLOC GRID");
152 strcpy(labels[ CMD_BUMP], "BUMPER TEST");
153 strcpy(labels[ CMD_INIT_COMM], "INIT ROBOT COMM");
154 strcpy(labels[ CMD_SEND_MSG], "SEND MESSAGE");
155 strcpy(labels[ CMD_RECEIVE_MSG], "RECEIVE MESSAGE");
156
157 strcpy(labels[ CMD_EXIT], "EXIT");
158
159 //BEGIN SCOUT THESIS CHANGE
160 sprintf(Control_Panel, "Control [%d] Panel", r.id);
161
162 control_window.init_panel(CON_WIN_LEFT, CON_WIN_TOP,
163 CON_BUTTON_WIDTH,
164 CON_BUTTON_HEIGHT, Control_Panel,
165 CON_LAB_WIDTH, CON_LAB_HEIGHT, CON_NUM_CMD,
166 CON_COLS, CON_ROWS, labels);
167 control_window.draw();
168

```



```

169         // Initialize evidence grid window
170
171         grid_window = new window(EGWIN_LEFT, EGWIN_TOP, EGWIN_RIGHT,
172 EGWIN_BOTTOM,
173             "Evidence Grid");
174         grid_window->set_window(EGWIN_WC_LEFT, EGWIN_WC_BOTTOM,
175 EGWIN_WC_RIGHT,
176             EGWIN_WC_TOP);
177         grid_window->iconify();
178
179         // Initialize navigation grid window
180
181         //     nav_window = new window(NAV_WIN_LEFT, NAV_WIN_TOP,
182 NAV_WIN_RIGHT,
183             NAV_WIN_BOTTOM, "Navigation Grid");
184         //     nav_window->set_window(NAV_WIN_WC_LEFT, NAV_WIN_WC_BOTTOM,
185 NAV_WIN_WC_RIGHT,
186             NAV_WIN_WC_TOP);
187         //     nav_window->iconify();
188
189         // Initialize global evidence grid window
190
191         sprintf(Global_Grid, "Global [%d] Grid", r.id);
192
193         global_window = new window(GLOBAL_WIN_LEFT, GLOBAL_WIN_TOP,
194             GLOBAL_WIN_RIGHT, GLOBAL_WIN_BOTTOM,
195             Global_Grid);
196         // END SCOUT THESIS CHANGE
197         global_window->set_window(GLOBAL_WIN_WC_LEFT, GLOBAL_WIN_WC_BOTTOM,
198             GLOBAL_WIN_WC_RIGHT, GLOBAL_WIN_WC_TOP);
199         //     global_window->iconify();
200
201         // Initialize evidence grid sensor models
202
203         //     cout << "Evidence grid: <disabled>" << endl;
204
205         table_init();
206         model_init(&sonar_smd, &sonar_clear_smd);
207
208         // Initialize evidence grids
209
210         grid_init(&egrid, 0.0, 0.0);
211         grid_init(&old_grid, 0.0, 0.0);
212
213         grid_init_nav(&nav_grid, 0.0, 0.0);
214
215         grid_init_global(&global_grid, 0.0, 0.0);
216         grid_init_global(&old_global, 0.0, 0.0);
217         grid_init_global(&edge_grid, 0.0, 0.0);
218
219         // Initialize moving obstacles
220
221         for (i = 0; i < NUM_MOB; i++) {
222             mob_list[i].rand_init();
223         }
224
225         // Reset timers
226

```

```

227     timer = 0;
228
229     // Initialize file pointers
230
231     logfile = NULL;
232
233     // Turn on all sensors
234
235     r.sonar_on();
236     r.ir_on();
237     r.laser_on();
238
239     // Initialize cell count
240
241     cell_count = 0;
242
243     // BUMPER FIX INITIALIZATION
244
245     for (i = 0; i < NUM_TOUCH; i++) {
246         bumped[i] = 0;
247     }
248 }
249
250 /***** USER CONTROL FUNCTIONS *****/
251
252 void agent::control(void)
253 {
254     // Main control loop
255
256     int quit = 0;
257
258     do {
259         quit = user_command();
260     }
261     while (!quit);
262 }
263
264
265 void agent::power_check(void)
266 {
267     // Check battery power
268
269     char vostr[ STRLEN];    // Voice string
270
271     gs();
272
273     cpu_volt = (double) (int) (voltCpuGet() * 100.0) / 100.0;
274     motor_volt = (double) (int) (voltMotorGet() * 100.0) / 100.0;
275
276     // cout << "CPU voltage = " << cpu_volt << " : motor voltage = " <<
277     motor_volt
278     //      << endl;
279
280     // cout << "CPU voltage = " << voltCpuGet() << " : motor voltage = "
281     //      << voltMotorGet() << endl;
282
283     if (cpu_volt < cpu_min) {
284         cpu_min = cpu_volt;

```

```

285     if (cpu_volt < CPU_DANGER_VOLTAGE) {
286         sprintf(vostr, "Danger, Danger: C P U voltage is %.2f.\n",
287 cpu_volt);
288         cout << vostr;
289         tk(vostr);
290     }
291     else if (cpu_volt < CPU_FULL_VOLTAGE) {
292         sprintf(vostr, "Warning: C P U voltage is %.2f.\n", cpu_volt);
293         cout << vostr;
294         tk(vostr);
295     }
296 }
297
298     if (motor_volt < motor_min) {
299         motor_min = motor_volt;
300         if (motor_volt < MOTOR_DANGER_VOLTAGE) {
301             sprintf(vostr, "Danger, Danger: Motor voltage is %.2f.\n",
302 motor_volt);
303             cout << vostr;
304             tk(vostr);
305         }
306         else if (motor_volt < MOTOR_FULL_VOLTAGE) {
307             sprintf(vostr, "Warning: Motor voltage is %.2f.\n", motor_volt);
308             cout << vostr;
309             tk(vostr);
310         }
311     }
312 }
313
314 int agent::user_command(void)
315 {
316     // Execute user command (if any)
317
318     int quit = 0;           // Set to 1 for exit command
319     int command;           // Command code
320
321     // power_check();
322
323     control_window.refresh();
324     command = control_window.scan_panel();
325
326     switch(command) {
327     case CMD_EXPLORE:
328         exploration_lls();
329         break;
330     case CMD_NAV:
331         navigation();
332         break;
333     case CMD_NAV_KBD:
334         navigation_keyboard();
335         break;
336     case CMD_SAVE:
337         save_net();
338         break;
339     case CMD_LOAD:
340         load_net();
341         break;
342     case CMD_REDRAW:

```

```

343     pnet.display();
344     break;
345 case CMD_BUILD_GRID:
346     r.update();
347     grid_clear(egrid);
348     clear_robot(egrid, 0, 0);
349     sonar_sweep_seq(egrid);
350 //     laser_sweep_seq(egrid);
351     grid_display(grid_window, egrid);
352     break;
353 case CMD_SAVE_GRID:
354     save_grid(egrid);
355     break;
356 case CMD_LOAD_GRID:
357     load_grid(&egrid);
358     r.update();
359     grid_display(grid_window, egrid);
360     break;
361 case CMD_GRID:
362     r.update();
363     grid_display(grid_window, egrid);
364     break;
365 case CMD_CLEAR:
366     grid_copy(old_grid, egrid);
367     grid_clear(egrid);
368     grid_display(grid_window, egrid);
369     break;
370 case CMD_CLEAR_ROBOT:
371     grid_copy(old_grid, egrid);
372     r.update();
373     clear_robot(egrid, r.x, r.y);
374     grid_display(grid_window, egrid);
375     break;
376 case CMD_SONAR_SCAN:
377     grid_copy(old_grid, egrid);
378     r.update();
379 // SCOUT THESIS CHANGE - in line below changed r.turret to r.theta
380     sonar_scan(sonar_smd, sonar_clear_smd, egrid, r.x, r.y, r.theta);
381     grid_display(grid_window, egrid);
382     break;
383 case CMD_SONAR_SWEEP:
384     grid_copy(old_grid, egrid);
385     clear_robot(egrid, 0, 0);
386     sonar_sweep_seq(egrid);
387     grid_display(grid_window, egrid);
388     break;
389 case CMD_SONAR_SWEEP_ABS:
390     grid_copy(old_grid, egrid);
391     r.update();
392     clear_robot(egrid, r.x, r.y);
393     sonar_sweep_abs_seq(egrid);
394     grid_display(grid_window, egrid);
395     break;
396 case CMD_CLEAR_SONAR:
397     grid_copy(old_grid, egrid);
398     grid_clear(egrid);
399     r.update();
400     clear_robot(egrid, 0, 0);

```

```

401     sonar_sweep_seq(egrid);
402     grid_display(grid_window, egrid);
403     break;
404 case CMD_LASER_SCAN:
405     grid_copy(old_grid, egrid);
406     r.update();
407     // Replaced r.turret with r.theta in line below
408     laser_scan(egrid, r.x, r.y, r.theta); // SCOUT THESIS change for
409 Scout with fixed body laser
410     grid_display(grid_window, egrid);
411     break;
412 case CMD_LASER_SWEEP:
413     grid_copy(old_grid, egrid);
414     r.update();
415     laser_sweep_seq(egrid);
416     grid_display(grid_window, egrid);
417     break;
418 case CMD_LASER_SWEEP_ABS:
419     grid_copy(old_grid, egrid);
420     r.update();
421     laser_sweep_abs_seq(egrid);
422     grid_display(grid_window, egrid);
423     break;
424 case CMD_CLEAR_LASER:
425     grid_copy(old_grid, egrid);
426     grid_clear(egrid);
427     r.update();
428     laser_sweep_seq(egrid);
429     grid_display(grid_window, egrid);
430     break;
431 case CMD_LLS_SCAN:
432     grid_copy(old_grid, egrid);
433     r.update();
434     lls_scan(sonar_smd, sonar_clear_smd, egrid, r.x, r.y, r.theta); //
435 SCOUT THESIS - see change above
436     grid_display(grid_window, egrid);
437     break;
438 case CMD_LLS_SWEEP:
439     grid_copy(old_grid, egrid);
440     r.update();
441     clear_robot(egrid, 0, 0);
442     lls_sweep_abs_seq(egrid);
443     grid_display(grid_window, egrid);
444     break;
445 case CMD_LLS_SWEEP_ABS:
446     grid_copy(old_global, global_grid);
447     r.update();
448     clear_robot(global_grid, 0, 0);
449     lls_sweep_seq(global_grid);
450     grid_display_global(global_grid);
451     break;
452 case CMD_CLEAR_LLS:
453     grid_copy(old_grid, egrid);
454     grid_clear(egrid);
455     r.update();
456     clear_robot(egrid, 0, 0);
457     lls_sweep_seq(egrid);
458     grid_display(grid_window, egrid);

```



```

459     break;
460 case CMD_GRID_UNDO:
461     grid_copy(egrid, old_grid);
462     grid_display(grid_window, egrid);
463     break;
464 case CMD_GRID_IDENT:
465     grid_ident_seq();
466     break;
467 case CMD_CENTER:
468     center_seq();
469     break;
470 case CMD_PLACE_MAP:
471     map_seq();
472     break;
473 case CMD_PLACE_IDENT:
474     ident_seq();
475     break;
476 case CMD_PLACE_GRID:
477     display_place_grid();
478     break;
479 case CMD_LOCAL_NAV:
480     local_navigation();
481     break;
482 case CMD_ADD_PLACE:
483     pnet.add_place();
484     break;
485 case CMD_EDIT_PLACE:
486     pnet.edit_place();
487     break;
488 case CMD_ADD_EDIT_LINK:
489     pnet.add_edit_link();
490     break;
491 case CMD_DELETE_LINK:
492     pnet.delete_link();
493     break;
494 case CMD_CLEAR_GLOBAL:
495     grid_copy(old_global, global_grid);
496     grid_clear(global_grid);
497     grid_display_global(global_grid);
498     num_front = 0;
499     num_visit = 0;
500     num_inac = 0;
501     break;
502 case CMD_SAVE_GLOBAL:
503     save_grid(global_grid);
504     break;
505 case CMD_LOAD_GLOBAL:
506     load_grid(&global_grid);
507     r.update();
508     grid_display_global(global_grid);
509     break;
510 case CMD_DISPLAY_GLOBAL:
511     grid_display_global(global_grid);
512     break;
513 case CMD_GLOBAL_UNDO:
514     grid_copy(global_grid, old_global);
515     grid_display_global(global_grid);
516     break;

```

```

517 case CMD_INTEGRATE_GRID:
518     integrate_grid(global_grid, egrid, (double) r.x / 120.0,
519                     (double) r.y / 120.0, (double) r.theta / 10.0);
520     grid_display_global(global_grid);
521     break;
522 case CMD_FIND_FRONTIERS:
523     find_frontiers();
524     break;
525 case CMD_DISPLAY_EDGES:
526     grid_display_global(global_grid);
527     grid_display_edges(region_map);
528     break;
529 case CMD_DISPLAY_FRONTIERS:
530     grid_display_global(global_grid);
531     grid_display_regions(region_map);
532     display_region_centroids(0.0, 0.0);
533     // display_robot_region_centroids();
534     break;
535 case CMD_GOTO_FRONTIER:
536     frontier_navigate();
537     break;
538 case CMD_UPDATE_NAV_GRID:
539     update_nav_grid();
540     break;
541 case CMD_DETECT_CORRIDORS:
542     detect_corridors();
543     display_corridors();
544     break;
545 case CMD_CONNECT_CL:
546     connect_cl();
547     break;
548 case CMD_SEND_CL_GRID:
549     send_cl_grid();
550     break;
551 case CMD_BUMP:
552     bump_test();
553     break;
554 case CMD_INIT_COMM:
555     init_robot_comm();
556     break;
557 case CMD_SEND_MSG:
558     user_send_robot_message();
559     break;
560 case CMD_RECEIVE_MSG:
561     user_receive_robot_message();
562     break;
563 case CMD_EXIT:
564     terminate();
565     quit = 1;
566     break;
567 }
568 return(quit);
569 }
570
571 void agent::terminate(void)
572 {
573     // End session
574 }

```

```

575     int i;
576
577     // Delete mobstacles
578
579     for (i = 0; i < NUM_MOB; i++) {
580         mob_list[i].del_obs();
581     }
582
583     // Shut down robot
584
585     r.shutdown();
586 }
587
588 int agent::iscan(void)
589 {
590     // Scan for interrupt
591
592     int command;
593
594     control_window.refresh();
595     command = control_window.scan_panel();
596     if ((command == CMD_STOP) || (command == CMD_EXIT)) {
597         st();
598         return(ABORT);
599     }
600     else {
601         return(OK);
602     }
603 }
604
605 /***** BEHAVIOR CONTROL SYSTEMS *****/
606
607 void agent::bump_test(void)
608 {
609     grid_display_global(global_grid);
610
611     while(iscan() != ABORT) {
612         update();
613         bump_halt();
614     }
615 }
616
617 void agent::manual_exploration(void)
618 {
619     // Map territory under manual control
620
621     int net_status; // Place net changed status
622
623     timer = 0;
624     behavior_mode = EXPLORE_MODE;
625
626     // BEGIN SCOUT THESIS CHANGE
627     scout_vm(0, 0); // Necessary hack so robot will start moving later
628     // SCOUT THESIS CHANGE - changed pr to vm
629     // END SCOUT THESIS CHANGE
630
631     manual_exploration_seq();
632 }

```

```

633
634 void agent::exploration(void)
635 {
636     // Explore territory
637
638     behavior_mode = EXPLORE_MODE;
639
640     exploration_seq();
641 }
642
643 void agent::exploration_lls(void)
644 {
645     // Explore territory using laser-limited sonar
646
647     char comm_str[ STRLEN];          // Contloc communication string
648
649     behavior_mode = EXPLORE_LLS_MODE;
650
651     // Set relocalization interval
652
653     sprintf(comm_str, "reloc_distance = %d", EXPLORE_RELOC_DISTANCE);
654     cout << "comm_str = <" << comm_str << ">" << endl;
655     write_comm(COMM_CHANNEL, comm_str, strlen(comm_str) + 1);
656
657     // Exploration sequence
658
659     exploration_lls_seq();
660 }
661
662 void agent::reactive_exploration(void)
663 {
664     // Explore territory reactively
665
666     int net_status; // Place net changed status
667     // char logname[ STRLEN];      // Log file name
668     // char apnname[ STRLEN];      // APN file name
669
670     timer = 0;
671     behavior_mode = EXPLORE_MODE;
672
673     /* do {
674         cout << "Enter log file name ==> ";
675         cin >> logname;
676
677         logfile = new ofstream(logname);
678         if (logfile == NULL) {
679             cout << "Unable to open log file <" << logname << ">." << endl;
680         }
681     }
682     while(logfile == NULL);
683
684     cout << "Enter APN file name ==> ";
685     cin >> apnname;*/
686
687     // reset();
688     // pnet.clear_net();
689
690     update();

```

```

691 net_status = pnet.place_learn((double) r.x, (double) r.y,
692                               (double) r.theta / 10.0);
693 if (net_status & NEW_PLACE) {
694     map_seq();
695 }
696
697 reactive_exploration_seq();
698
699 // logfile->close();
700 // pnet.save(apnname);
701 }
702
703 void agent::multi_exploration(void)
704 {
705     // Explore territory (multiple trials)
706
707     char prefix[ STRLEN]; // Filename prefixes
708     char logname[ STRLEN]; // Log filename
709     char apnname[ STRLEN]; // APN filename
710     int trial_index; // Trial index
711     int trial_start; // Index for initial trial
712     int trial_end; // Index for last trial
713     int rand_x, rand_y, rand_heading; // Random initial position
714
715     behavior_mode = EXPLORE_MODE;
716
717     cout << "Enter filename prefix ==> ";
718     cin >> prefix;
719
720     cout << "Enter starting trial number ==> ";
721     cin >> trial_start;
722
723     cout << "Enter ending trial number ==> ";
724     cin >> trial_end;
725
726     for(trial_index = trial_start; trial_index <= trial_end;
727 trial_index++) {
728         sprintf(logname, "%s%d.log", prefix, trial_index);
729         sprintf(apnname, "%s%d.apn", prefix, trial_index);
730
731         logfile = new ofstream(logname);
732         if (logfile == NULL) {
733             cout << "Unable to open log file <" << logname << ">." << endl;
734         }
735         else {
736             cout << "Opening log file <" << logname << ">." << endl;
737         }
738
739         reset();
740         pnet.clear_net();
741
742         // Set random initial position
743
744         rand_x = irand(PWIN_WC_LEFT + RAND_MARGIN, PWIN_WC_RIGHT -
745 RAND_MARGIN);
746         rand_y = irand(PWIN_WC_BOTTOM + RAND_MARGIN, PWIN_WC_TOP -
747 RAND_MARGIN);
748         rand_heading = irand(0, 3600);

```



```

749     place_robot(rand_x, rand_y, rand_heading, rand_heading);
750
751     // Hack to make sure robot isn't teleported into wall
752
753     // BEGIN SCOUT THESIS CHANGE
754     scout_vm(1, 0);    // TEMP FIX- changed pr to vm
755     scout_vm(-1, 0);   // TEMP FIX - changed pr to vm
756     // END SCOUT THESIS CHANGE
757
758     update();
759     pnet.place_learn((double) r.x, (double) r.y, (double) r.theta /
760 10.0);
761
762     exploration_seq();
763
764     if (logfile != NULL) {
765         logfile->close();
766     }
767     pnet.save(apnname);
768 }
769 }
770
771 void agent::multi_reactive_exploration(void)
772 {
773     // Explore territory reactively (multiple trials)
774
775     char prefix[ STRLEN]; // Filename prefixes
776     char logname[ STRLEN]; // Log filename
777     char apnname[ STRLEN]; // APN filename
778     int trial_index;       // Trial index
779     int trial_start;       // Index for initial trial
780     int trial_end;        // Index for last trial
781
782     behavior_mode = EXPLORE_MODE;
783
784     cout << "Enter filename prefix ==> ";
785     cin >> prefix;
786
787     cout << "Enter starting trial number ==> ";
788     cin >> trial_start;
789
790     cout << "Enter ending trial number ==> ";
791     cin >> trial_end;
792
793     for(trial_index = trial_start; trial_index <= trial_end;
794 trial_index++) {
795         sprintf(logname, "%s%d.log", prefix, trial_index);
796         sprintf(apnname, "%s%d.apn", prefix, trial_index);
797
798         logfile = new ofstream(logname);
799         if (logfile == NULL) {
800             cout << "Unable to open log file <" << logname << ">." << endl;
801         }
802         else {
803             cout << "Opening log file <" << logname << ">." << endl;
804         }
805
806         reset();

```

```

807     pnet.clear_net();
808
809     update();
810     pnet.place_learn((double) r.x, (double) r.y, (double) r.theta /
811 10.0);
812
813     reactive_exploration_seq();
814
815     if (logfile != NULL) {
816         logfile->close();
817     }
818     pnet.save(apnname);
819 }
820 }
821
822 void agent::navigation(void)
823 {
824     // Navigate to destination specified with mouse
825
826     char comm_str[STRLEN]; // Contloc communication string
827     char vostr[STRLEN];    // Voice string
828     double gx, gy; // Destination point (world coords)
829
830     // Wait for user to click on destination in global window
831
832     grid_display_global(global_grid);
833
834     while(global_window->world_mouse(gx, gy) == 0);
835
836     sprintf(vostr, "Navigating to %d, %d.\n", (int) gx, (int) gy);
837     cout << vostr;
838     tk(vostr);
839
840     // Mark destination in window
841
842     global_window->set_color("red");
843     global_window->display_circle(gx, gy, CENTROID_MARK_RADIUS);
844     global_window->display_line(gx - CENTROID_MARK_RADIUS, gy,
845                               gx + CENTROID_MARK_RADIUS, gy);
846     global_window->display_line(gx, gy - CENTROID_MARK_RADIUS,
847                               gx, gy + CENTROID_MARK_RADIUS);
848     global_window->set_color("black");
849
850     // Set relocation interval
851
852     sprintf(comm_str, "reloc_distance = %d", NAV_RELOC_DISTANCE);
853     cout << "comm_str = <" << comm_str << ">" << endl;
854     write_comm(COMM_CHANNEL, comm_str, strlen(comm_str) + 1);
855
856     // Navigate to destination
857
858     refresh_all();
859     path_nav_seq(gx, gy);
860
861     r.move_to_xy((int) gx, (int) gy);
862     r.face_angle(0);
863
864     tk(""); // Sometimes garbage gets stuck in the voice buffer

```

```

865
866     sprintf(vostr, "Arrived at destination.\n");
867     cout << vostr;
868     tk(vostr);
869 }
870
871 void agent::navigation_keyboard(void)
872 {
873     // Navigate to destination specified with keyboard
874
875     char comm_str[ STRLEN];      // Contloc communication string
876     char vostr[ STRLEN];        // Voice string
877     double gx, gy;              // Destination point (world coords)
878     double gtheta;              // Destination orientation
879
880     // Ask user to enter destination
881
882     cout << "Enter destination (x, y, theta) (1/10 in, 1/10 deg) ==> ";
883     cin >> gx >> gy >> gtheta;
884
885     sprintf(vostr, "Navigating to %d, %d (%d).\n", (int) gx, (int) gy,
886             (int) gtheta);
887     cout << vostr;
888     tk(vostr);
889
890     // Mark destination in window
891
892     grid_display_global(global_grid);
893
894     global_window->set_color("red");
895     global_window->display_circle(gx, gy, CENTROID_MARK_RADIUS);
896     global_window->display_line(gx - CENTROID_MARK_RADIUS, gy,
897                               gx + CENTROID_MARK_RADIUS, gy);
898     global_window->display_line(gx, gy - CENTROID_MARK_RADIUS,
899                               gx, gy + CENTROID_MARK_RADIUS);
900     global_window->set_color("black");
901
902     // Set relocation interval
903
904     sprintf(comm_str, "reloc_distance = %d", NAV_RELOC_DISTANCE);
905     cout << "comm str = <" << comm_str << ">" << endl;
906     write_comm(COMM_CHANNEL, comm_str, strlen(comm_str) + 1);
907
908     // Navigate to destination
909
910     refresh_all();
911     path_nav_seq(gx, gy);
912
913     r.move_to_xy((int) gx, (int) gy);
914     r.face_angle((int) gtheta);
915
916     tk("");      // Sometimes garbage gets stuck in the voice buffer
917
918     sprintf(vostr, "Arrived at destination.\n");
919     cout << vostr;
920     tk(vostr);
921 }
922

```

```

923 void agent::local_navigation(void)
924 {
925     // Navigate to local coordinate point
926
927     int x, y;                // Local destination coordinates
928
929     cout << "Enter destination point (x, y) ==> ";
930     cin >> x >> y;
931
932     local_nav_seq(x, y);
933 }
934
935 void agent::frontier_navigate(void)
936 {
937     // Navigate to frontier centroid
938
939     int front_index;         // Index of destination frontier
940
941     if (num_front == 0) {
942         cout << "No frontiers detected." << endl;
943         return;
944     }
945
946     do {
947         cout << "Enter frontier index ==> ";
948         cin >> front_index;
949         if ((front_index < 0) || (front_index >= num_front)) {
950             cout << "Unknown frontier -- must be in range [0.." << num_front
951 << "]" . "
952             << endl;
953         }
954     }
955     while((front_index < 0) || (front_index >= num_front));
956
957     frontier_nav_seq(front_index);
958 }
959
960 /***** BEHAVIORAL SEQUENCERS *****/
961
962 void agent::manual_exploration_seq(void)
963 {
964     // Manual exploration sequencer
965
966     int net_status; // Place net changed status
967
968     cout << "Exploring under manual control..." << endl;
969
970     do {
971         update();
972         net_status = pnet.place_learn((double) r.x, (double) r.y,
973                                     (double) r.theta / 10.0);
974
975         if (net_status & NEW_PLACE) {
976             cout << "Stop." << endl;
977             tk("Stop.");
978             st();
979             ws(1, 1, 1, 5);
980

```

```

981         map_seq();
982     }
983 }
984 while(iscan() != ABORT);
985
986 cout << "Exploration complete." << endl;
987 }
988
989 void agent::exploration_seq(void)
990 {
991     // Exploration sequencer
992
993     int front_index = 0; // Frontier destination index
994     int nav_status = OK; // Navigation status
995
996     cout << "Exploring..." << endl;
997     tk("Exploring.");
998
999     update();
1000     clear_robot(global_grid, r.x, r.y);
1001     sonar_sweep_abs_seq(global_grid);
1002
1003     find_frontiers();
1004
1005     while((num_front > 0) && (nav_status != ABORT) && (front_index != -1))
1006     {
1007         front_index = closest_frontier((double) r.x, (double) r.y);
1008
1009         if (front_index != -1) {
1010             nav_status = frontier_nav_seq(front_index);
1011             // clear_robot(global_grid, r.x, r.y);
1012             // sonar_sweep_seq(global_grid);
1013             find_frontiers();
1014         }
1015     }
1016
1017     cout << "Exploration complete." << endl;
1018     tk("Exploration complete.");
1019 }
1020
1021 void agent::exploration_lls_seq(void)
1022 {
1023     // Exploration sequencer using laser-limited sonar
1024
1025     char local_filename [ STRLEN]; // Filename for local grid
1026     char local_posinfo [ STRLEN]; // Position info for local grid
1027     file
1028     char global_filename[ STRLEN]; // Filename for global grid
1029     char global_posinfo[ STRLEN]; // Position info for global grid
1030     file
1031     char message[ STRLEN]; // Message for multirobot communications
1032
1033     double tx = 0.0, ty = 0.0; // Registration translation vector
1034     double ttheta = 0.0; // Registration rotation
1035     double score; // Registration score for local
1036     grid
1037
1038

```



```

1039 int front_index = 0; // Frontier destination index
1040 int nav_status = OK; // Navigation status
1041 int occ; // Number of occupied cells in global grid
1042 int unocc; // Number of unoccupied cells in global grid
1043
1044 cout << "Exploring..." << endl;
1045 tk("Exploring.");
1046
1047
1048
1049 // NEW SCOUT THESIS CHANGE below
1050 // If robot is robot 1 it is the SERVER robot and will send its global
1051 map out to
1052 // the other CLIENT robots
1053 // if robot is not number 1 then it is a CLIENT robot and will only
1054 write its
1055 // local scan to file
1056 // in this way I hope to slow down error buildup in the map
1057
1058 if (r.id == 1) {
1059     sprintf(global_filename, "global%d.eg", r.id);
1060
1061     // Sweep from initial position and find frontiers
1062
1063     update();
1064     clear_robot(global_grid, r.x, r.y);
1065
1066 // BEGIN SCOUT THESIS CHANGE
1067 // instead of using laser limited sonar use just the sonars
1068
1069 // lls_sweep_abs_seq(global_grid); // commented out for Scout
1070 sonar_sweep_abs_seq(global_grid); // use sonars only to explore
1071 // END SCOUT THESIS CHANGE
1072
1073 // grid_display(grid_window, egrid);
1074
1075 // Save global grid
1076
1077 sprintf(global_posinfo, "%d %d %d", 0, 0, 0);
1078 save_grid_file(global_grid, global_filename, global_posinfo);
1079
1080 // Notify other robot
1081
1082 if (multi_mode) {
1083     send_robot_message(global_filename);
1084 }
1085
1086 // Display global grid
1087
1088 grid_display_global(global_grid);
1089
1090 // Send grid to continuous localization
1091
1092 grid_count_occ(global_grid, &occ, &unocc);
1093 cout << "Global grid cells: mapped = " << occ + unocc
1094     << " : occupied = " << occ << endl;
1095 if (occ >= CONTLOC_MIN_OCC) {

```

```

1097     send_cl_grid();
1098 }
1099
1100 // Check for new map from other robot
1101
1102 if (multi_mode) {
1103     integrate_remote_map();
1104 }
1105
1106 // Find initial frontiers
1107
1108 find_frontiers();
1109
1110 while(nav_status != ABORT) {
1111     if (num_front > 0) {
1112         // Navigate to closest frontier (index = -1 if inaccessible or
1113         visited)
1114
1115         front_index = closest_frontier((double) r.x, (double) r.y);
1116         if (front_index != -1) {
1117             nav_status = frontier_nav_seq(front_index);
1118         }
1119     }
1120
1121     if ((num_front == 0) || (front_index == -1)) {
1122         if (iscan() == ABORT) { // add check for interrupts from
1123         control panel
1124             nav_status = ABORT;
1125         }
1126         else {
1127             cout << "No frontiers remaining, sweeping sensors..." << endl;
1128             tk("No frontiers, sweeping.");
1129             nav_status = NO_FRONTIERS;
1130         }
1131     }
1132
1133     if ((nav_status != ABORT) && (nav_status != NO_PATH)) {
1134         clear_robot(global_grid, r.x, r.y);
1135     }
1136 // BEGIN SCOUT THESIS CHANGE
1137 // instead of using laser limited sonar use just the sonars
1138
1139 //     lls_sweep_abs_seq(global_grid); // commented out for Scout
1140 //     sonar_sweep_abs_seq(global_grid);
1141 // END SCOUT THESIS CHANGE
1142
1143 //     grid_display(grid_window, egrid);
1144
1145 // Save global grid
1146
1147 sprintf(global_posinfo, "%d %d %d", 0, 0, 0);
1148 save_grid_file(global_grid, global_filename, global_posinfo);
1149
1150 // Notify other robot
1151
1152 if (multi_mode) {
1153     send_robot_message(global_filename);
1154 }

```

```

1155
1156 // Display global grid
1157
1158 grid_display_global(global_grid);
1159
1160 // Send grid to continuous localization
1161
1162 grid_count_occ(global_grid, &occ, &unocc);
1163
1164 cout << "Global grid cells: mapped = " << occ + unocc
1165      << " : occupied = " << occ << endl;
1166
1167 if (occ >= CONTLOC_MIN_OCC) {
1168     send_cl_grid();
1169 }
1170
1171 // Check for new map from other robot
1172
1173 if (multi_mode) {
1174     integrate_remote_map();
1175 }
1176
1177 // Find new frontiers
1178
1179 find_frontiers();
1180 }
1181 }
1182
1183 } // close for if r.id==1
1184
1185
1186
1187 // NEW MAJOR SCOUT THESIS change
1188 // now handle the case of the CLIENT robots that just write their
1189 // local maps
1190
1191 else { // r.id != 1
1192
1193     sprintf(local_filename, "local%d.eg", r.id);
1194
1195     // Sweep from initial position and find frontiers
1196
1197     update();
1198     grid_clear(egrid); // clear the old local grid prior to scanning
1199     clear_robot(egrid, 0, 0); // mark the cells under the robot as
1200     unoccupied
1201     // clear_robot(global_grid, r.x, r.y);
1202
1203     // BEGIN SCOUT THESIS CHANGE
1204     // instead of using laser limited sonar use just the sonars
1205
1206     // lls_sweep_abs_seq(global_grid); // commented out for Scout
1207     // sonar_sweep_abs_seq(global_grid); // use sonars only to explore in
1208     global position
1209     sonar_sweep_seq(egrid); // use sonars only to make local scan
1210     centered around robot
1211     // END SCOUT THESIS CHANGE
1212

```

```

1213     // grid_display(grid_window, egrid);
1214
1215     // Register local grid with global grid - necessary when using robot
1216     base position
1217     // for scanning vice global position
1218
1219     tx = (double) r.x / 120.0;
1220     ty = (double) r.y / 120.0;
1221     ttheta = 0.0;
1222
1223     // Save local grid
1224
1225     sprintf(local_posinfo, "%d %d %d", r.x, r.y, 0);
1226     save_grid_file(egrid, local_filename, local_posinfo);
1227
1228     // Notify other robot
1229
1230     if (multi_mode) {
1231         send_robot_message(local_filename);
1232     }
1233
1234     // Integrate local grid with global grid
1235     integrate_grid(global_grid, egrid, tx, ty, ttheta);
1236
1237
1238     // Display global grid
1239     grid_display_global(global_grid);
1240
1241     // Send grid to continuous localization
1242
1243     grid_count_occ(global_grid, &occ, &unocc);
1244     cout << "Global grid cells: mapped = " << occ + unocc
1245           << " : occupied = " << occ << endl;
1246     if (occ >= CONTLOC_MIN_OCC) {
1247         send_cl_grid();
1248     }
1249
1250     // Check for new map from other robot
1251
1252     if (multi_mode) {
1253         integrate_remote_map();
1254     }
1255
1256     // Find initial frontiers
1257
1258     find_frontiers();
1259
1260     while(nav_status != ABORT) {
1261         if (num_front > 0) {
1262             // Navigate to closest frontier (index = -1 if inaccessible or
1263             visited)
1264
1265             front_index = closest_frontier((double) r.x, (double) r.y);
1266             if (front_index != -1) {
1267                 nav_status = frontier_nav_seq(front_index);
1268             }
1269         }
1270

```

```

1271     if ((num_front == 0) || (front_index == -1)) {
1272         if (iscan() == ABORT) { // check for interrupts from
1273 control panel
1274         nav_status = ABORT;
1275     }
1276     else {
1277         cout << "No frontiers remaining, sweeping sensors..." << endl;
1278         tk("No frontiers, sweeping.");
1279         nav_status = NO_FRONTIERS;
1280     }
1281 }
1282
1283 if ((nav_status != ABORT) && (nav_status != NO_PATH)) {
1284     grid_clear(egrid);
1285     clear_robot(egrid, 0, 0);
1286
1287 // BEGIN SCOUT THESIS CHANGE
1288 // instead of using laser limited sonar use just the sonars
1289
1290 //     lls_sweep_abs_seq(global_grid); // commented out for Scout
1291 //     sonar_sweep_abs_seq(global_grid);
1292     sonar_sweep_seq(egrid);
1293 // END SCOUT THESIS CHANGE
1294
1295     // grid_display(grid_window, egrid);
1296
1297 // Register local grid with global grid - necessary when using robot
1298 base position
1299 // for scanning vice global position
1300
1301     tx = (double) r.x / 120.0;
1302     ty = (double) r.y / 120.0;
1303     ttheta = 0.0;
1304
1305
1306
1307     // Save local grid
1308
1309     sprintf(local_posinfo, "%d %d %d", r.x, r.y, 0);
1310     save_grid_file(egrid, local_filename, local_posinfo);
1311
1312     // Notify other robot
1313
1314     if (multi_mode) {
1315         send_robot_message(local_filename);
1316     }
1317
1318 // Integrate local grid with global grid
1319     integrate_grid(global_grid, egrid, tx, ty, ttheta);
1320
1321     // Display global grid
1322
1323     grid_display_global(global_grid);
1324
1325     // Send grid to continuous localization
1326
1327     grid_count_occ(global_grid, &occ, &unocc);
1328

```



```

1329     cout << "Global grid cells: mapped = " << occ + unocc
1330         << " : occupied = " << occ << endl;
1331
1332     if (occ >= CONTLOC_MIN_OCC) {
1333         send_cl_grid();
1334     }
1335
1336     // Check for new map from other robot
1337
1338     if (multi_mode) {
1339         integrate_remote_map();
1340     }
1341
1342     // Find new frontiers
1343
1344     find_frontiers();
1345 }
1346 }
1347
1348 } // close for else r.id != 1
1349
1350 // END NEW MAJOR THESIS change
1351
1352
1353
1354     cout << "Exploration complete." << endl;
1355     tk("Exploration complete.");
1356 }
1357
1358
1359
1360 void agent::reactive_exploration_seq(void)
1361 {
1362     // Reactive exploration sequencer
1363
1364     cout << "Exploring reactively..." << endl;
1365     tk("Exploring");
1366
1367     do {
1368         update();
1369
1370         set_defaults();
1371         if (reactive_explore_behaviors() == 0) {
1372             execute();
1373         }
1374     }
1375     while((iscan() != ABORT) && (timer <= TRIAL_LENGTH));
1376
1377     cout << "Exploration complete." << endl;
1378 }
1379
1380 int agent::navigation_seq(void)
1381 {
1382     // Follow path to destination
1383     // (returns ABORT if interrupt or error, OK otherwise)
1384
1385     char vostr[ STRLEN]; // Voice string
1386     int suc[ PLACE_UNITS]; // Succesor list

```

```

1387     int gx, gy;                // Gateway location
1388     int arrived = 0;           // 1 when arrived at destination, 0
1389 otherwise
1390     int nav_status = OK;        // Navigation status
1391     int i;
1392
1393     behavior_mode = NAVIGATION_MODE;
1394
1395     cout << "Navigating to place [" << destin << "]" << endl;
1396     sprintf(vostr, "Navigating to place %d.\n", destin);
1397     tk(vostr);
1398
1399     //     ident_seq();
1400
1401     //     cout << "Enter current place index ==> ";
1402     //     cin >> pnet.windex;
1403
1404     while((pnet.windex != destin) && (nav_status != ABORT)) {
1405         pnet.find_paths(destin, suc);
1406         pnet.display();
1407
1408         cout << endl << "Place transition list:" << endl;
1409         for (i = 0; i < pnet.num_units; i++) {
1410             cout << "[" << i << "]" --> "[" << suc[i] << "]" << endl;
1411         }
1412         cout << endl;
1413
1414         if (suc[pnet.windex] == -1) {
1415             cout << "navigate_seq: No way to get from place [" <<
1416 pnet.windex
1417             << "]" to place [" << destin << "]" << endl;
1418             return(ABORT);
1419         }
1420
1421         if (pnet.link[pnet.windex][suc[pnet.windex]] == NULL) {
1422             cout << "navigate_seq: Nonexistent link [" << pnet.windex
1423             << "]" --> "[" << suc[pnet.windex] << "]" << endl;
1424             return(ABORT);
1425         }
1426
1427         gx = pnet.link[pnet.windex][suc[pnet.windex]]->gateway_x;
1428         gy = pnet.link[pnet.windex][suc[pnet.windex]]->gateway_y;
1429
1430         cout << "Navigating to [" << pnet.windex << "]" --> ["
1431             << suc[pnet.windex] << "]" gateway at (" << gx << ", " << gy
1432 << ")."
1433             << endl;
1434
1435         nav_status = local_nav_seq(gx, gy);
1436
1437         if (nav_status != ABORT) {
1438             ident_seq();
1439         }
1440     }
1441
1442     if (nav_status == ABORT) {
1443         cout << "Aborted." << endl;
1444     }

```

```

1445     else {
1446         cout << "Arrived at destination place [" << destin << "]" << endl;
1447     }
1448     return(nav_status);
1449 }
1450
1451 int agent::local_nav_seq(int gx, int gy)    // Local destination
1452 coordinates
1453 {
1454     // Local navigation sequencer
1455
1456     char vostr[ STRLEN];    // Voice string
1457     double dist;            // Distance from goal
1458     double min_dist;        // Minimum distance to goal so far
1459     double bearing;         // Bearing to goal
1460     int nav_status = 0;      // 1: arrived, 0: otherwise
1461     int stall_count = 0;     // Timesteps since progress made toward
1462     goal
1463
1464     update();
1465
1466     dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1467     // cout << "Distance from goal = " << dist << " inches" << endl;
1468
1469     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1470     // cout << "Bearing to goal = " << bearing << endl;
1471
1472     min_dist = dist;
1473
1474     sprintf(vostr, "Navigating to %d %d.\n", gx, gy);
1475     // tk(vostr);
1476     cout << vostr;
1477
1478     if ((iscan() != ABORT) && (dist > LOCAL_NAV_TOLERANCE)) {
1479         r.face_angle_fast((int) (bearing * 10.0));
1480     }
1481
1482     while((iscan() != ABORT) && (dist > LOCAL_NAV_TOLERANCE) &&
1483           (stall_count < STALL_TIMEOUT)) {
1484
1485         update();
1486
1487         bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1488         if (angle_diff(bearing, (double) r.theta / 10.0) > LOCAL_TIP_ANGLE)
1489         {
1490             r.face_angle_fast((int) (bearing * 10.0));
1491         }
1492         else {
1493             set_defaults();
1494             nav_status = local_navigation_behaviors(gx, gy);
1495             execute();
1496         }
1497
1498         dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1499         // cout << "Distance from goal = " << dist << " inches" << endl;
1500
1501         if (dist < min_dist) {

```

```

1503     min_dist = dist;
1504     stall_count = 0;
1505 }
1506 else {
1507     stall_count++;
1508     if (stall_count % 5 == 0) {
1509         sprintf(vostr, "Stalled for %d steps.\n", stall_count);
1510         cout << vostr;
1511         tk(vostr);
1512     }
1513 }
1514 }
1515
1516 st();
1517
1518 if (stall_count >= STALL_TIMEOUT) {
1519     sprintf(vostr, "Navigation timeout.\n",
1520         stall_count);
1521     cout << vostr;
1522     tk(vostr);
1523     return(TIMEOUT);
1524 }
1525 else if (dist > LOCAL_NAV_TOLERANCE) {
1526     cout << "Aborted." << endl;
1527     tk("Aborted.");
1528     return(ABORT);
1529 }
1530
1531 cout << "Arrived." << endl;
1532 // tk("Arrived.");
1533 return(OK);
1534 }
1535
1536 int agent::path_local_nav_seq(path p,          // Path to follow
1537                               int &waypoint)    // Index of next waypoint
1538 {
1539     // Local navigation sequencer for path following
1540
1541     char message[ STRLEN ] ;           // Message from other robot
1542     char vostr[ STRLEN ] ;             // Voice string
1543     double dist;                       // Distance from goal
1544     double min_dist;                   // Minimum distance to goal so far
1545     double close_dist;                 // Distance to closest waypoint
1546     double bearing;                    // Bearing to goal
1547     int gx, gy;                        // Waypoint coordinates
1548     int nav_status = 0;                 // 1: arrived, 0: otherwise
1549     int stall_count = 0;                // Timesteps since progress made toward
1550     goal
1551     int close_index = waypoint; // Index of closest waypoint
1552     int i;
1553
1554     // Set goal to next waypoint
1555
1556     gx = p.x[ waypoint ] ;
1557     gy = p.y[ waypoint ] ;
1558
1559     // Update robot state
1560

```

```

1561     update();
1562
1563     // Find distance/bearing to goal
1564
1565     dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1566     // cout << "Distance from goal = " << dist << " inches" << endl;
1567
1568     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1569     // cout << "Bearing to goal = " << bearing << endl;
1570
1571     min_dist = dist;
1572
1573     sprintf(vostr, "Navigating to %d %d.\n", gx, gy);
1574     // tk(vostr);
1575     cout << vostr;
1576
1577     // Find distance to closest waypoint
1578
1579     close_dist = closest_waypoint(p, r.x, r.y, waypoint, close_index);
1580
1581     while((iscan() != ABORT) && (close_dist > LOCAL_NAV_TOLERANCE) &&
1582           (stall_count < STALL_TIMEOUT)) {
1583
1584         // Update robot state
1585
1586         update();
1587
1588         // Stop if collision
1589
1590         bump_halt();
1591
1592         // Realign if turret is misaligned with base
1593
1594         maintain_alignment();
1595
1596         // Find bearing to goal
1597
1598         bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1599
1600         cout << "goal [" << waypoint << "]" : bearing = " << bearing
1601              << " : dist = " << dist << " | closest [" << close_index
1602              << "]" : dist = " << close_dist << endl;
1603
1604         // Orient toward open corridor and advance
1605
1606         goal_corridor_orient(gx, gy);
1607         corridor_advance();
1608
1609         // Check distance from goal
1610
1611         dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1612
1613         if (dist < min_dist) {
1614
1615             // If progress has been made, reset stall counter
1616
1617             min_dist = dist;
1618             stall_count = 0;

```



```

1619     }
1620     else {
1621
1622         // Otherwise, increment stall counter
1623
1624         stall_count++;
1625         if (stall_count % 5 == 0) {
1626             sprintf(vostr, "Stalled for %d steps.\n", stall_count);
1627             cout << vostr;
1628             tk(vostr);
1629         }
1630     }
1631
1632     // Find distance to closest waypoint
1633
1634     close_dist = closest_waypoint(p, r.x, r.y, waypoint, close_index);
1635 }
1636
1637 // Determine why navigation terminated
1638
1639 if (stall_count >= STALL_TIMEOUT) { // Timeout
1640     sprintf(vostr, "Navigation timeout.\n",
1641             stall_count);
1642     cout << vostr;
1643     tk(vostr);
1644     return(TIMEOUT);
1645 }
1646 else if (close_dist > LOCAL_NAV_TOLERANCE) { // User abort
1647     cout << "Aborted." << endl;
1648     tk("Aborted.");
1649     return(ABORT);
1650 }
1651
1652 cout << "Arrived." << endl; // Success
1653 // tk("Arrived.");
1654
1655 // Advance to next waypoint on path after closest waypoint
1656
1657 waypoint = close_index + 1;
1658
1659 return(OK);
1660 }
1661
1662 int agent::local_cont_nav_seq(int gx, int gy) // Local destination
1663 coords
1664 {
1665     // Local navigation sequencer (continuous motion)
1666
1667     char vostr[ STRLEN]; // Voice string
1668     double dist; // Distance from goal
1669     double min_dist; // Minimum distance to goal so far
1670     double bearing; // Bearing to goal
1671     int nav_status = 0; // 1: arrived, 0: otherwise
1672     int stall_count = 0; // Timesteps since progress made toward
1673     goal
1674
1675     update();
1676

```

```

1677 dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1678 // cout << "Distance from goal = " << dist << " inches" << endl;
1679
1680 bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1681 // cout << "Bearing to goal = " << bearing << endl;
1682
1683 min_dist = dist;
1684
1685 sprintf(vostr, "Navigating to %d %d.\n", gx, gy);
1686 // tk(vostr);
1687 cout << vostr;
1688
1689 if (angle_diff(bearing, (double) r.theta / 10.0) > LOCAL_TIP_ANGLE) {
1690     r.face_angle_fast((int) (bearing * 10.0));
1691 }
1692
1693 while((iscan() != ABORT) && (dist > LOCAL_NAV_TOLERANCE) &&
1694     (stall_count < STALL_TIMEOUT)) {
1695
1696     update();
1697
1698     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1699     if (angle_diff(bearing, (double) r.theta / 10.0) > LOCAL_TIP_ANGLE)
1700 {
1701         r.face_angle_fast((int) (bearing * 10.0));
1702     }
1703     else {
1704         set_defaults();
1705         nav_status = local_navigation_behaviors(gx, gy);
1706         execute();
1707     }
1708
1709     dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1710     // cout << "Distance from goal = " << dist << " inches" << endl;
1711
1712     if (dist < min_dist) {
1713         min_dist = dist;
1714         stall_count = 0;
1715     }
1716     else {
1717         stall_count++;
1718         if (stall_count % 5 == 0) {
1719             sprintf(vostr, "Stalled for %d steps.\n", stall_count);
1720             cout << vostr;
1721             tk(vostr);
1722         }
1723     }
1724 }
1725
1726 // st();
1727
1728 if (stall_count >= STALL_TIMEOUT) {
1729     sprintf(vostr, "Navigation timeout.\n",
1730         stall_count);
1731     cout << vostr;
1732     tk(vostr);
1733     return(TIMEOUT);
1734 }

```

```

1735     else if (dist > LOCAL_NAV_TOLERANCE) {
1736         cout << "Aborted." << endl;
1737         tk("Aborted.");
1738         return(ABORT);
1739     }
1740
1741     cout << "Arrived." << endl;
1742     // tk("Arrived.");
1743     return(OK);
1744 }
1745
1746 int agent::local_nav_seq_alt(int gx, int gy,      // Goal coordinates
1747                             int ax, int ay)      // Alternate goal coordinates
1748 {
1749     // Local navigation sequencer (with alternate goal)
1750
1751     char vostr[ STRLEN];          // Voice string
1752     double dist;                  // Distance from goal
1753     double alt_dist;              // Distance from alternate goal
1754     double min_dist;              // Minimum distance to goal so far
1755     double bearing;               // Bearing to goal
1756     int nav_status = 0;           // 1: arrived, 0: otherwise
1757     int stall_count = 0;          // Timesteps since progress made toward
1758     goal
1759     int interrupt;                // Interrupt code
1760
1761     update();
1762
1763     dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1764     // cout << "Distance from goal = " << dist << " inches" << endl;
1765
1766     alt_dist = hypot((double) (ax - r.x), (double) (ay - r.y)) / 10.0;
1767     // cout << "Distance from alternate goal = " << alt_dist << "
1768     inches"
1769     // << endl;
1770
1771     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
1772     // cout << "Bearing to goal = " << bearing << endl;
1773
1774     min_dist = dist;
1775
1776     sprintf(vostr, "Navigating to %d %d.\n", gx, gy);
1777     // tk(vostr);
1778     cout << vostr;
1779
1780     cout << "Alternate goal: (" << ax << ", " << ay << ")" << endl;
1781
1782     r.face_angle_fast((int) (bearing * 10.0));
1783
1784     while(((interrupt = iscan()) != ABORT) && (dist > LOCAL_NAV_TOLERANCE)
1785     &&
1786         (stall_count < STALL_TIMEOUT) && (alt_dist > LOCAL_NAV_TOLERANCE))
1787     {
1788
1789         update();
1790
1791         bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;

```

```

1792     if (angle_diff(bearing, (double) r.theta / 10.0) > LOCAL_TIP_ANGLE)
1793     {
1794         r.face_angle_fast((int) (bearing * 10.0));
1795     }
1796     else {
1797         set_defaults();
1798         nav_status = local_navigation_behaviors(gx, gy);
1799         execute();
1800     }
1801
1802     dist = hypot((double) (gx - r.x), (double) (gy - r.y)) / 10.0;
1803     //      cout << "Distance from goal = " << dist << " inches" << endl;
1804
1805     alt_dist = hypot((double) (ax - r.x), (double) (ay - r.y)) / 10.0;
1806     //      cout << "Distance from alternate goal = " << alt_dist << "
1807 inches"
1808     //      << endl;
1809
1810     if (dist < min_dist) {
1811         min_dist = dist;
1812         stall_count = 0;
1813     }
1814     else {
1815         stall_count++;
1816         if (stall_count % 5 == 0) {
1817             sprintf(vostr, "Stalled for %d steps.\n", stall_count);
1818             cout << vostr;
1819             tk(vostr);
1820         }
1821     }
1822 }
1823
1824 st();
1825
1826 if (stall_count >= STALL_TIMEOUT) {
1827     sprintf(vostr, "Navigation timeout.\n",
1828         stall_count);
1829     cout << vostr;
1830     tk(vostr);
1831     return(TIMEOUT);
1832 }
1833
1834 if (interrupt == ABORT) {
1835     cout << "Aborted." << endl;
1836     tk("Aborted.");
1837     return(ABORT);
1838 }
1839
1840 if (dist <= LOCAL_NAV_TOLERANCE) {
1841     cout << "Arrived." << endl;
1842     //      tk("Arrived.");
1843     return(OK);
1844 }
1845
1846 if (alt_dist <= LOCAL_NAV_TOLERANCE) {
1847     cout << "Arrived at alternate goal." << endl;
1848     //      tk("Arrived at alternate goal.");
1849     return(ALT);

```

```

1850     }
1851
1852     cout << "local_nav_seq_alt: Illegal termination." << endl;
1853     exit(-1);
1854 }
1855
1856 void agent::center_seq(void)
1857 {
1858     // Move to center of current place
1859
1860     int cx, cy;           // Place center
1861     int ctheta;           // Place orientation
1862
1863     if (pnet.windex == -1) {
1864         cout << "Unable to center at unknown location." << endl;
1865         return;
1866     }
1867
1868     cx = (int) pnet.unit[pnet.windex].x;
1869     cy = (int) pnet.unit[pnet.windex].y;
1870     ctheta = (int) (pnet.unit[pnet.windex].theta * 10.0);
1871
1872     /*    cx = 0;
1873          cy = 0;
1874          ctheta = 0;*/
1875
1876     r.move_to_xy(cx, cy);
1877     r.face_angle(ctheta);
1878     // BEGIN SCOUT THESIS CHANGE
1879     // comment out call for turret alignment - is not necessary for SCOUT
1880     //    r.turret_align();
1881     // END SCOUT THESIS CHANGE
1882 }
1883
1884 int agent::path_nav_seq(double gx, double gy)    // World coords of goal
1885 {
1886     // Navigate to goal by planning and following path
1887
1888     path nav_path;           // Navigation path
1889     int nav_status;          // Navigation status
1890     int path_found;          // 1 if path found, 0 otherwise
1891     int next_lls_point = NAV_LLS_SWEEP_INTERVAL; // Waypoint for next LLS
1892     sweep
1893     int i, j;
1894
1895     path_found = path_plan(gx, gy, nav_path);
1896     if (!path_found) {
1897         return(NO_PATH);
1898     }
1899
1900     // cout << "Press <enter> to continue." << endl;
1901     // cin.get();
1902
1903     for (i = 1; i < nav_path.length; ) {
1904         nav_status = path_local_nav_seq(nav_path, i);
1905
1906         // Stop immediately at end of path
1907         // (so the robot doesn't crash if the goal is next to a wall)

```



```

1908     if (i == nav_path.length) {
1909         st();
1910         cout << "Stopping at path's end." << endl;
1911     }
1912
1913     if (i >= next_lls_point) {
1914         // Sweep laser at intervals (for contloc)
1915         lls_sweep_seq(egrid);
1916
1917         next_lls_point += NAV_LLS_SWEEP_INTERVAL;
1918     }
1919
1920     if (nav_status == ABORT) {                // User aborted
1921         return(ABORT);
1922     }
1923
1924     if (nav_status == ALT) {                // Arrived unexpectedly at goal
1925         display_path(nav_path, TRAV_PATH_COLOR, global_window);
1926         return(OK);
1927     }
1928
1929     if (nav_status == TIMEOUT) {            // Navigation timeout
1930         return(TIMEOUT);
1931     }
1932
1933     // Mark traversed path segment in global window
1934
1935     global_window->set_color(TRAV_PATH_COLOR);
1936     for (j = 0; j < i - 1; j++) {
1937         global_window->display_line(nav_path.x[j], nav_path.y[j],
1938                                     nav_path.x[j + 1], nav_path.y[j + 1]);
1939     }
1940     global_window->flush();
1941     global_window->set_color("black");
1942
1943     // Mark traversed path segment in robot window
1944
1945     //     for (j = 0; j < i - 1; j++) {
1946     //         draw_line(nav_path.x[j], nav_path.y[j],
1947     //                 nav_path.x[j + 1], nav_path.y[j + 1],
1948     //                 ROBOT_TRAV_PATH_COLOR + 2);
1949     //     }
1950 }
1951
1952 st();
1953
1954 return(OK);                // Arrived at goal
1955 }
1956
1957 int agent::frontier_path_nav_seq(int front_index)    // Frontier index
1958 {
1959     // Navigate to frontier by planning and following path
1960
1961     path nav_path;    // Navigation path
1962     double gx, gy;    // World coords of frontier centroid
1963     int nav_status;    // Navigation status
1964     int path_found;    // 1 if path found, 0 otherwise
1965     int i, j;

```

```

1966
1967 gx = frontiers[ front_index].x;
1968 gy = frontiers[ front_index].y;
1969
1970 path_found = frontier_path_plan(gx, gy, front_index, nav_path);
1971 if (!path_found) {
1972     return(NO_PATH);
1973 }
1974
1975 update();
1976
1977 // cout << "Press <enter> to continue." << endl;
1978 // cin.get();
1979
1980 for (i = 1; i < nav_path.length; ) {
1981     nav_status = path_local_nav_seq(nav_path, i);
1982
1983     // Stop immediately at end of path
1984     // (so the robot doesn't crash if the goal is next to a wall)
1985     if (i == nav_path.length) {
1986         st();
1987         cout << "Stopping at path's end." << endl;
1988     }
1989
1990     if (nav_status == ABORT) {                // User aborted
1991         return(ABORT);
1992     }
1993
1994     if (nav_status == ALT) {                // Arrived unexpectedly at goal
1995         display_path(nav_path, TRAV_PATH_COLOR, global_window);
1996         return(OK);
1997     }
1998
1999     if (nav_status == TIMEOUT) {            // Navigation timeout
2000         return(TIMEOUT);
2001     }
2002
2003     // Mark traversed path segment in global window
2004
2005     global_window->set_color(TRAV_PATH_COLOR);
2006     for (j = 0; j < i - 1; j++) {
2007         global_window->display_line(nav_path.x[j], nav_path.y[j],
2008                                     nav_path.x[j + 1], nav_path.y[j + 1]);
2009     }
2010     global_window->flush();
2011     global_window->set_color("black");
2012
2013     // Mark traversed path segment in robot window
2014
2015     //     for (j = 0; j < i - 1; j++) {
2016     //         draw_line(nav_path.x[j], nav_path.y[j],
2017     //                 nav_path.x[j + 1], nav_path.y[j + 1],
2018     //                 ROBOT_TRAV_PATH_COLOR + 2);
2019     //     }
2020 }
2021
2022 return(OK);                // Arrived at goal
2023 }

```

```

2024
2025 void agent::sonar_sweep_seq(Map3D map)
2026 {
2027     // Rotate sonar sensors and scan
2028
2029     int i;
2030
2031     for (i = 0; i < SONAR_SWEEP_WIDTH; i += SONAR_SWEEP_STEP) {
2032         update();
2033         // THESIS SCOUT CHANGE send r.theta not r.turret for SCOUT
2034         sonar_scan(sonar_smd, sonar_clear_smd, map, r.x, r.y, r.theta);
2035         // cout << "r.theta=" << r.theta << endl; // show robot heading
2036         value
2037         // grid_display_global(map); // TEMP FIX test map display - shows
2038         updated display after each scan
2039
2040         // BEGIN SCOUT THESIS CHANGE
2041         scout_vm(0, SONAR_SWEEP_STEP * 10); // Rotate the robot, - not the
2042         turret - changed pr to vm
2043         // ws(1, 1, 0, 5); // TEMP FIX comment this line out and try
2044         sleep instead
2045         sleep(3); // SCOUT THESIS CHANGE added this line as test **PAUSE
2046         robot at intervals**
2047     }
2048
2049     // SCOUT THESIS CHANGE - do not rotate Scout back as line below would do
2050     // hopefully this will decrease the odometry error buildup
2051     // scout_pr(0, SONAR_SWEEP_WIDTH * -10); // Rotate the robot back
2052     // ws(1, 1, 0, 5); // TEMP FIX comment this line out and try sleep
2053     instead
2054     // sleep(3); // TEMP FIX added this line as test
2055     // END SCOUT THESIS CHANGE
2056     update();
2057 }
2058
2059 void agent::sonar_sweep_abs_seq(Map3D map)
2060 {
2061     // Rotate sonar sensors and scan (absolute coordinates)
2062
2063     int i;
2064
2065     for (i = 0; i < SONAR_SWEEP_WIDTH; i += SONAR_SWEEP_STEP) {
2066         update();
2067         sonar_scan_abs(sonar_smd, sonar_clear_smd, map, r.x, r.y, r.theta);
2068         // cout << "r.theta=" << r.theta << endl; // show robot heading
2069         value
2070         // grid_display_global(map); // TEMP FIX test map display - shows
2071         updated display after each scan
2072         // TEMP FIX send r.theta not r.turret for SCOUT
2073
2074         // BEGIN SCOUT THESIS CHANGE
2075         scout_vm(0, SONAR_SWEEP_STEP * 10); // changed pr to vm
2076         // ws(1, 1, 0, 5); // TEMP FIX comment this line out and try
2077         sleep cmd instead
2078         sleep(1); // TEMP FIX added this line as test
2079     }
2080

```

```

2081 // SCOUT THESIS CHANGE - do not rotate Scout back as line below would
2082 do
2083 // hopefully this will decrease the odometry error buildup
2084 // scout_pr(0, SONAR_SWEEP_WIDTH * -10);
2085 // ws(1, 1, 0, 5); // TEMP FIX comment out this line and try sleep
2086 cmd instead
2087 // sleep(3); // TEMP FIX added this line as test
2088 // END SCOUT THESIS CHANGE
2089 update();
2090 }
2091
2092 void agent::laser_sweep_seq(Map3D map)
2093 // Rotate laser scanner and scan
2094 {
2095     int scans = 0;
2096
2097     // BEGIN SCOUT THESIS CHANGE
2098     scout_vm(0, 3600); // just in case we ever put a laser on the Scout
2099     // TEMP FIX - use vm instead of pr
2100     // END SCOUT THESIS CHANGE
2101     r.wait_start();
2102
2103     while(State[ STATE_VEL_TURRET] > 0) {
2104         laser_scan(map, r.x, r.y, r.theta); // TEMP FIX for SCOUT if it
2105         ever has a fixed laser -yeh right
2106         if (realtime_display) {
2107             display_robot(global_window, State[ 34] , State[ 35] , State[ 36] ,
2108             State[ 37] );
2109         }
2110         scans++;
2111     }
2112
2113     cout << scans << " scans completed : avg scan interval = "
2114         << 360.0 / (double) scans << " degrees" << endl;
2115 }
2116
2117 void agent::laser_sweep_abs_seq(Map3D map)
2118 // Rotate laser scanner and scan (absolute coordinates)
2119 {
2120     int scans = 0;
2121
2122     // BEGIN SCOUT THESIS CHANGE
2123     scout_vm(0, 3600); // TEMP FIX - use vm instead of pr
2124     // END SCOUT THESIS CHANGE
2125     r.wait_start();
2126
2127     while(State[ STATE_VEL_TURRET] > 0) {
2128         laser_scan_abs(map, r.x, r.y, r.theta); //TEMP FIX for SCOUT with
2129         fixed laser
2130         if (realtime_display) {
2131             display_robot(global_window, State[ 34] , State[ 35] , State[ 36] ,
2132             State[ 37] );
2133         }
2134         scans++;
2135     }
2136
2137     cout << scans << " scans completed : avg scan interval = "
2138         << 360.0 / (double) scans << " degrees" << endl;

```

```

2139 }
2140
2141 void agent::lls_sweep_seq(Map3D map)
2142 // Laser-limited sonar sweep
2143 {
2144     int scans = 0;
2145
2146     // SCOUT NOTE - do not know how Scout handles sp command
2147     sp(DEFAULT_SPEED, DEFAULT_TURN_RATE, 0); // TEMP FIX for SCOUT
2148
2149     r.sonar_single(0);
2150     r.ir_single(0);
2151     // BEGIN SCOUT THESIS CHANGE
2152     scout_vm(0, 3600); // TEMP FIX- try vm instead of pr commands for
2153     SCOUT
2154     // END SCOUT THESIS CHANGE
2155     r.wait_start();
2156
2157     while(State[ STATE_VEL_TURRET] > 0) {
2158         lls_scan(sonar_smd, sonar_clear_smd, map, r.x, r.y, r.theta); //
2159         TEMP FIX for SCOUT
2160         if (realtime_display) {
2161             display_robot(global_window, State[ 34], State[ 35], State[ 36],
2162             State[ 37] );
2163         }
2164         scans++;
2165     }
2166
2167     cout << scans << " scans completed : avg scan interval = "
2168         << 360.0 / (double) scans << " degrees" << endl;
2169
2170     r.ir_on();
2171     r.sonar_on();
2172     r.set_default_velocity();
2173 }
2174
2175 void agent::lls_sweep_abs_seq(Map3D map)
2176 // Laser-limited sonar sweep (absolute coordinates)
2177 {
2178     int scans = 0;
2179
2180     // SCOUT NOTE - do not know how Scout would handle sp command
2181     sp(DEFAULT_SPEED, DEFAULT_TURN_RATE, 0); // TEMP FIX for SCOUT
2182
2183     r.sonar_single(0);
2184     r.ir_single(0);
2185     // BEGIN SCOUT THESIS CHANGE
2186     scout_vm(0, 3600); // TEMP FIX - try vm instead of pr commands for
2187     SCOUT
2188     // END SCOUT THESIS CHANGE
2189     r.wait_start();
2190
2191     while(State[ STATE_VEL_TURRET] > 0) {
2192         lls_scan_abs(sonar_smd, sonar_clear_smd, map, r.x, r.y, r.theta);
2193         // TEMP FIX for SCOUT
2194         if (realtime_display) {
2195             display_robot(global_window, State[ 34], State[ 35], State[ 36],
2196             State[ 37] );

```



```

2197     }
2198     scans++;
2199 }
2200
2201 cout << scans << " scans completed : avg scan interval = "
2202     << 360.0 / (double) scans << " degrees" << endl;
2203
2204 r.ir_on();
2205 r.sonar_on();
2206 r.set_default_velocity();
2207 }
2208
2209 void agent::map_seq(void)
2210 {
2211     // Build local grid
2212
2213     char vostr[ STRLEN ];    // Voice string
2214
2215     st();
2216     // BEGIN SCOUT THESIS CHANGE
2217     ws(1, 1, 0, 5);
2218     // END SCOUT THESIS CHANGE
2219
2220     update();
2221     pnet.place_learn((double) r.x, (double) r.y, (double) r.theta / 10.0);
2222
2223     // sprintf(vostr, "Building map for place %d.\n", pnet.windex);
2224     // cout << vostr;
2225     // tk(vostr);
2226
2227     grid_clear(pnet.unit[ pnet.windex ].lgrid);
2228
2229     clear_robot(pnet.unit[ pnet.windex ].lgrid, 0, 0);
2230     sonar_sweep_seq(pnet.unit[ pnet.windex ].lgrid);
2231     // laser_sweep_seq(pnet.unit[ pnet.windex ].lgrid);
2232
2233     grid_display(grid_window, pnet.unit[ pnet.windex ].lgrid);
2234
2235     cout << "Map complete." << endl;
2236 }
2237
2238 void agent::ident_seq(void)
2239 {
2240     // Place identification sequencer
2241
2242     // Build grid
2243
2244     r.update();
2245     grid_clear(egrid);
2246
2247     clear_robot(egrid, 0, 0);
2248     sonar_sweep_seq(egrid);
2249     // laser_sweep_seq(egrid);
2250
2251     grid_display(grid_window, egrid);
2252
2253     // Identify grid
2254

```

```

2255     grid_ident_seq();
2256 }
2257
2258 void agent::grid_ident_seq(void)
2259 {
2260     // Grid identification sequencer
2261
2262     char comm_str[ STRLEN];           // Communications string
2263     char vostr[ STRLEN];              // Voice string
2264     double tx, ty;                   // Translation vector
2265     double ttheta;                   // Rotation
2266     int ix, iy, itheta;              // Identified position
2267     int ident;                       // Place ident index
2268
2269     ident = pnet.best_match(egrid);
2270
2271     cout << "Untransformed best match = [" << ident << "]" << endl;
2272
2273     ident = pnet.best_trans_match(egrid, tx, ty, ttheta);
2274     cout << endl;
2275
2276     cout << "Transformed best match = [" << ident << "]" (" <<
2277 pnet.unit[ ident].x
2278     << ", " << pnet.unit[ ident].y << ")" << endl;
2279     cout << "Transformation = (" << tx << ", " << ty << ") [" << ttheta <<
2280 "]"
2281     << endl;
2282
2283     // Update dead reckoning
2284
2285     gs();
2286     ix = (int) (tx * 120.0 + 0.5);
2287     iy = (int) (ty * 120.0 + 0.5);
2288     itheta = wrap(r.theta + (int) (ttheta * 10.0 + 0.5), 0, 3599);
2289
2290     cout << endl;
2291     cout << "place = " << ident << " : x = " << ix << " : y = " << iy
2292     << " : theta = " << itheta << endl;
2293
2294     sprintf(vostr, "I am at place %d.\n", ident);
2295     tk(vostr);
2296
2297     pnet.windex = ident;
2298     pnet.display();
2299
2300     r.x = ix + (int) (pnet.unit[ ident].x + 0.5);
2301     r.y = iy + (int) (pnet.unit[ ident].y + 0.5);
2302     r.theta = itheta;
2303
2304     place_robot(r.x, r.y, r.theta, r.theta);
2305
2306     // sprintf(comm_str, "%s/grid%d %d %d %d", apndir, ident, ix, iy,
2307     itheta);
2308     // cout << "comm str = <" << comm_str << ">" << endl;
2309     // write_comm(COMM_CHANNEL, comm_str, strlen(comm_str) + 1);
2310
2311     // while(read_comm(COMM_CHANNEL, comm_str, 80) < 1);
2312     // cout << "reply = < " << comm_str << ">" << endl;

```

```

2313 }
2314
2315 int agent::frontier_nav_seq(int front_index)    // Frontier destination
2316 index
2317 {
2318     // Navigate to selected frontier
2319
2320     int nav_status; // Navigation status
2321     char vostr[ STRLEN];    // Voice string
2322
2323     cout << "Navigating to frontier [" << front_index << "] -- centroid ("
2324         << (int) frontiers[ front_index].x << ", "
2325         << (int) frontiers[ front_index].y << ")" << endl;
2326
2327     sprintf(vostr, "Navigating to frontier %d.\n", front_index);
2328     tk(vostr);
2329
2330     // grid_display_global(global_grid);
2331     // grid_display_regions(region_map);
2332     // display_region_centroids(0.0, 0.0);
2333     // display_robot_region_centroids();
2334
2335     nav_status = frontier_path_nav_seq(front_index);
2336
2337     if (nav_status == ABORT) {
2338         return(ABORT);
2339     }
2340
2341     if (nav_status == OK) {
2342         sprintf(vostr, "Arrived at frontier %d.\n", front_index);
2343         cout << vostr;
2344         tk(vostr);
2345
2346         if (num_visit == MAX_FRONTIERS) {
2347             cout << "Visited too many frontiers (>" << MAX_FRONTIERS << ")."
2348 << endl;
2349             exit(-1);
2350         }
2351
2352         front_visit[ num_visit].x = frontiers[ front_index].x;
2353         front_visit[ num_visit].y = frontiers[ front_index].y;
2354         num_visit++;
2355     }
2356
2357     if ((nav_status == TIMEOUT) || (nav_status == NO_PATH)) {
2358         if (num_inac > MAX_FRONTIERS) {
2359             cout << "frontier_nav_seq: Too many inaccessible frontiers (> " <<
2360             MAX_FRONTIERS << ")." << endl;
2361             exit(-1);
2362         }
2363
2364         sleep(1);
2365         sprintf(vostr, "Frontier %d is inaccessible.\n", front_index);
2366         cout << vostr;
2367         tk(vostr);
2368
2369         frontier_copy(front_inac[ num_inac], frontiers[ front_index]);
2370         num_inac++;

```

```

2371     }
2372
2373     return(nav_status);
2374 }
2375
2376 /***** BEHAVIOR SETS *****/
2377
2378 int agent::reactive_explore_behaviors(void)
2379 {
2380     // Behavior set for reactive exploration
2381
2382     // Returns 1 if new place mapped, 0 otherwise
2383
2384     int net_status = 0;
2385
2386     advance();
2387     avoid();
2388     bump_halt();
2389
2390     net_status = pnet.place_learn((double) r.x, (double) r.y,
2391                                   (double) r.theta / 10.0);
2392
2393     if (net_status & NEW_PLACE) {
2394         map_seq();
2395         return(1);
2396     }
2397
2398     return(0);
2399 }
2400
2401 int agent::navigation_behaviors(void)
2402 {
2403     // Behavior set for navigation
2404
2405     int nav_status; // 1 if active path link exists at current location,
2406                   // 0 otherwise
2407
2408     advance();
2409     maintain_heading();
2410     avoid();
2411     bump_halt();
2412
2413     nav_status = follow_path();
2414
2415     pnet.place_recall((double) r.x, (double) r.y, (double) r.theta / 10.0,
2416                      destin);
2417
2418     return(nav_status);
2419 }
2420
2421 int agent::local_navigation_behaviors(int gx, int gy)
2422 {
2423     // Behavior set for local navigation
2424
2425     int nav_status = 0; // 1: arrived, 0: otherwise
2426
2427     corridor_advance();
2428     return(nav_status);

```

```

2429 }
2430
2431 /***** UTILITY FUNCTIONS *****/
2432
2433 void agent::reset(void)
2434 {
2435     // Reset position and timer
2436
2437     dp(0, 0);
2438     da(0, 0);
2439
2440     timer = 0;
2441 }
2442
2443 void agent::set_defaults(void)
2444 {
2445     // Set default command values
2446
2447     speed_arb->clear();
2448     turn_arb->clear();
2449 }
2450
2451 void agent::update(void)
2452 {
2453     // Update robot state and moving obstacles
2454
2455     int i;
2456
2457     if (timer % 10 == 0) {
2458         cout << "Time = " << timer << endl;
2459         // power_check();
2460         // if (logfile != NULL) {
2461         //     *logfile << timer << " " << pnet.num_units << endl;
2462         // }
2463     }
2464
2465     r.update();
2466
2467     // for (i = 0; i < NUM_MOB; i++) {
2468     //     mob_list[i].update(r.x, r.y);
2469     // }
2470
2471     // clear_robot(global_grid, r.x, r.y);
2472
2473     if (realtime_display) {
2474         display_robot(global_window, r.x, r.y, r.theta, r.theta); // TEMP
2475     }
2476     // FIX for SCOUT
2477
2478     // sonar_print(egrid, 1);
2479
2480     timer++;
2481 }
2482
2483 void agent::execute(void)
2484 {
2485     // Send commands to robot
2486

```



```

2487     int speed_com, turn_com;
2488
2489     //     speed_window.display(speed_arb->votes);
2490     //     turn_window.display(turn_arb->votes);
2491
2492     speed_com = (int) speed_arb->command();
2493     turn_com = (int) (turn_arb->command() * 10.0);
2494
2495     if ((speed_com == 0) && (turn_com == 0)) {
2496         turn_com = (int) (rdrand(-RAND_TURN, RAND_TURN) * 10.0);
2497     //     cout << "Random turn <" << turn_com << ">" << endl;
2498     }
2499
2500     r.move(speed_com, turn_com);
2501
2502     home_dist += (int) speed_arb->command();
2503 }
2504
2505 /***** BEHAVIORS *****/
2506
2507 void agent::bump_halt(void)
2508 {
2509     // Go limp if bumper touched
2510
2511     // BEGIN SCOUT THESIS CHANGE
2512     // comment out the code below that was a hack for a bad bumper
2513     // rearrange code to match original code
2514
2515     char vostr[STRLEN]; // Voice string
2516     // int touch_offset; // Rotation offset for touch sensors
2517     // int abs_touch; // Absolute index of tripped bumper
2518     // int sleepflag = 0; // Do you sleep?
2519     int i;
2520
2521     if (r.touch.max() > 0) {
2522         lp(); // robot motors stop
2523
2524         for (i = 0; i < NUM_TOUCH; i++) {
2525             if (r.touch[i]) {
2526                 sprintf(vostr, "Contact on bumper %d.", i);
2527                 cout << vostr << endl;
2528                 tk(vostr);
2529             } // close if
2530         } // close for
2531
2532         sprintf(vostr, "Sleeping for %d seconds.", BUMP_SLEEP);
2533         cout << vostr << endl;
2534         tk(vostr);
2535
2536         sleep(BUMP_SLEEP);
2537     } // close if
2538 } // clode bump_halt
2539
2540
2541 // Below was all hack code for the procedure above
2542
2543 // HACK! On Coyote, ignore multiple bumps on same bumper.

```

```

2545 //
2546 // REMOVE THIS WHEN COYOTE'S BUMPER BOARD IS FIXED
2547 //
2548 // touch_offset = wrap((int) ((double) (r.theta + r.bumper_offset)
2549 //                      / (double) BUMPER_SEP + 0.5),
2550 //                      NUM_TOUCH);
2551 // abs_touch = wrap(i + touch_offset, NUM_TOUCH);
2552 //
2553 // if ((r.id == 1) || !bumped[abs_touch]) {
2554 //     lp();
2555 //     sprintf(vostr, "Contact on bumper %d.", abs_touch);
2556 //     cout << vostr << endl;
2557 //     tk(vostr);
2558 //     bumped[abs_touch] = 1;
2559 //     sleepflag = 1;
2560 // }
2561 // }
2562 // }
2563 //
2564 //
2565 // if (sleepflag) {
2566 //     sprintf(vostr, "Sleeping for %d seconds.", BUMP_SLEEP);
2567 //     cout << vostr << endl;
2568 //     tk(vostr);
2569 //
2570 //     sleep(BUMP_SLEEP);
2571 // }
2572 // }
2573 // }
2574
2575 // END SCOUT THESIS CHANGE
2576
2577
2578 // BEGIN SCOUT THESIS CHANGE
2579 // NOTE - the following procedures recoil and bump_recoil were written
2580 // for the Nomad 200 but are NOT implemented in the code
2581 // The major problem with them on the Nomad 200 is misalignment
2582 // of the turret and the base.
2583 // They should actually be easier to implement for the Nomad Scout
2584 // because of it lack of a turret bumpers will always be fixed in
2585 // relation
2586 // to the robot.
2587 // Using these would be better than just using the bump_halt routine
2588 // above which only stops the robot but does not get it away from the
2589 // obstacle
2590
2591 void agent::recoil(void)
2592 {
2593     // If touched in forward half, move backward and turn
2594
2595     double spd;
2596     double trn;
2597
2598     if (r.touch.max(15, 5) > 0) {
2599         spd = rdrand(-RECOIL_SPEED, 0.0);
2600         trn = rdrand(-RECOIL_TURN, RECOIL_TURN);
2601
2602         speed_arb->vote(spd, RECOIL_SPEED_SIGMA, RECOIL_WT);

```

```

2603     turn_arb->vote(trn, RECOIL_TURN_SIGMA, RECOIL_WT);
2604
2605     cout << "Recoiling back... (speed = " << spd << ", turn = " << trn
2606         << ")" << endl;
2607 }
2608 }
2609
2610 void agent::bump_recoil(void)
2611 {
2612     // If bumper contact, recoil away
2613
2614     char vostr[ STRLEN];    // Voice string
2615     double rel_angle;       // Relative angle from robot to bumper contact
2616     double touch_angle;     // Absolute angle from robot to bumper contact
2617     double tx, ty;         // Coords of bumper contact
2618     int contact_flag = 0;   // Contact indicator (0 = no, 1 = yes)
2619     int i;
2620
2621     for (i = 0; i < NUM_TOUCH; i++) {
2622         if (r.touch[ i]) {
2623             lp();           // Go limp
2624
2625             sprintf(vostr, "Contact on bumper %d.", i);
2626             tk(vostr);
2627
2628             // Compute contact angle
2629
2630             // NOTE - the BUMPER_SEP number here would have to be changed
2631             //           to accomodate the different bumper pattern of the Scout
2632             //           which is not evenly spaced around the robot
2633             rel_angle = (double) (i * BUMPER_SEP) / 10.0;
2634
2635             sprintf(vostr, "Relative angle %.0f.", rel_angle);
2636             cout << vostr << endl;
2637             tk(vostr);
2638
2639             if ((rel_angle <= 90.0) || rel_angle >= 270.0) {
2640                 // Recoil back if contact is in forward half of robot
2641
2642                 cout << "<<< RECOILING BACK" << endl;
2643                 tk("Recoiling back.");
2644
2645                 // BEGIN SCOUT THESIS CHANGE
2646                 scout_vm(-BUMP_RECOIL, 0); // TEMP FIX - change pr to vm
2647                 ws(1, 1, 0, 10); TEMP FIX - comment out the wait
2648                 // END SCOUT THESIS CHANGE
2649             }
2650             else {
2651                 // Recoil forward if contact is in rear half of robot
2652
2653                 cout << "RECOILING FORWARD >>>" << endl;
2654                 tk("Recoiling forward.");
2655
2656                 // BEGIN SCOUT THESIS CHANGE
2657                 scout_vm(BUMP_RECOIL, 0); // TEMP FIX - change pr to vm
2658                 ws(1, 1, 0, 10); TEMP FIX - comment out the wait
2659                 // END SCOUT THESIS CHANGE
2660             }

```

```

2661         contact_flag = 1;
2662     }
2663     break;          // Only recoil from one contact
2664 }
2665 }
2666
2667 // Update global grid for all contacts
2668
2669 if (contact_flag) {
2670     for (i = 0; i < NUM_TOUCH; i++) {
2671         if (r.touch[i]) {
2672             // Compute contact position
2673
2674 // NOTE - the BUMPER_SEP number here would have to be changed
2675 //         to accomodate the different bumper pattern of the Scout
2676 //         which is not evenly spaced around the robot
2677             rel_angle = (double) (i * BUMPER_SEP) / 10.0;
2678             touch_angle = angle_wrap((double) r.theta / 10.0 + rel_angle);
2679             tx = (double) r.x + ROBOT_RADIUS * 120.0 * cos(touch_angle *
2680 DEG2RAD);
2681             ty = (double) r.y + ROBOT_RADIUS * 120.0 * sin(touch_angle *
2682 DEG2RAD);
2683
2684             // Update global grid
2685
2686             set_location(global_grid, tx / 120.0, ty / 120.0, SONAR_HEIGHT,
2687 POS);
2688         }
2689     }
2690 }
2691
2692 grid_display_global(global_grid);
2693 }
2694 }
2695
2696 void agent::maintain_alignment(void)
2697 {
2698     // Realign turret if it is not aligned with base
2699
2700     double dev;          // Deviation between base and turret angles
2701     int align_turn; // Turn required to realign turret
2702
2703     // BEGIN SCOUT THESIS CHANGE
2704     // fake code into thinking nonexistent turret is aligned with base
2705     dev = 0.0; // fix for SCOUT
2706     // dev = angle_diff((double) r.theta / 10.0, (double) r.turret / 10.0);
2707
2708     if (dev > MAX_BASE_TURRET_DEV) {
2709         tk("Realigning.");
2710         st();
2711
2712         do {
2713             cout << "REALIGNING:  base = " << r.theta << " : turret = "
2714                  << r.turret << " : deviation = " << dev << endl;
2715
2716             align_turn =
2717                 (int) (angle_sgn_diff((double) r.theta / 10.0,
2718                                     (double) r.turret / 10.0)

```

```

2719         * 10.0 + 0.5);
2720     cout << "Realignment turn = <" << align_turn << ">" << endl;
2721
2722
2723 // NOTE - no turret on Scout to align, next two lines are ignored on
2724 Scout
2725     scout_vm(0, 0); // TEMP FIX for SCOUT
2726     ws(0, 0, 1, 100);
2727
2728     update();
2729     dev = 0.0; // fix for SCOUT
2730 //     dev = angle_diff((double) r.turret / 10.0, (double) r.theta /
2731 10.0);
2732 }
2733     while (dev > MAX_BASE_TURRET_DEV);
2734
2735     cout << "Realignment complete: base = " << r.theta << " : turret = "
2736     << r.turret << " : deviation = " << dev << endl;
2737 // END SCOUT THESIS CHANGE
2738 }
2739 }
2740
2741 int agent::advance(void)
2742 {
2743     // Move forward unless front is blocked (return 1 if blocked, 0
2744     otherwise)
2745
2746     int fwd_min; // Minimum forward distance
2747     int per_min; // Minimum peripheral distance
2748     double spd; // Desired speed
2749
2750     fwd_min = r.arc[ FWD ] ;
2751     per_min = r.range.min(FWD_RT, FWD_LF);
2752
2753     if ((fwd_min <= ADV_STOP_DIST) || (per_min <= ADV_PER_STOP_DIST)) {
2754         speed_arb->vote(0.0, ADV_SPEED_SIGMA, ADV_SPEED_WT);
2755         return(1);
2756     }
2757
2758     if ((fwd_min > ADV_SLOW_DIST) && (per_min > ADV_PER_SLOW_DIST)) {
2759         speed_arb->vote(ADV_SPEED, ADV_SPEED_SIGMA, ADV_SPEED_WT);
2760         return(0);
2761     }
2762
2763     spd = ADV_SPEED;
2764
2765     if (fwd_min <= ADV_SLOW_DIST) {
2766         spd = ADV_SPEED * (double) (fwd_min - ADV_STOP_DIST) /
2767         (double) (ADV_SLOW_DIST - ADV_STOP_DIST);
2768     }
2769
2770     if ((per_min <= ADV_PER_SLOW_DIST) && (spd > ADV_PER_SPEED)) {
2771         spd = ADV_PER_SPEED;
2772     }
2773
2774     speed_arb->vote(spd, ADV_SPEED_SIGMA, ADV_SPEED_WT);
2775     return(0);
2776 }

```



```

2777
2778 int agent::advance_slow(void)
2779 {
2780     // Move forward slowly unless front is blocked
2781     // (return 1 if blocked, 0 otherwise)
2782
2783     int fwd_min;           // Minimum forward distance
2784
2785     fwd_min = r.arc[ FWD ] ;
2786
2787     if (fwd_min > ADV_SLOW_STOP_DIST) {
2788         speed_arb->vote(ADV_SLOW_SPEED, ADV_SLOW_SPEED_SIGMA,
2789             ADV_SLOW_SPEED_WT);
2790         return(0);
2791     }
2792     else {
2793         speed_arb->vote(0.0, ADV_SLOW_SPEED_SIGMA, ADV_SLOW_SPEED_WT);
2794     }
2795 }
2796
2797 void agent::maintain_heading(void)
2798 {
2799     // Maintain current heading
2800
2801     turn_arb->vote(0.0, MH_TURN_SIGMA, MH_TURN_WT);
2802 }
2803
2804 void agent::avoid(void)
2805 {
2806     // Avoid nearby obstacles
2807
2808     int i;
2809     double wt;           // Voting weight for avoidance
2810     double theta; // Obstacle direction
2811
2812     for (i = 0; i < NUM_RANGE; i++) {
2813         if (r.range[ i ] < AVOID_DIST) {
2814             wt = AVOID_WT_FACTOR *
2815                 (double) (AVOID_DIST - r.range[ i ]) / (double) AVOID_DIST;
2816             theta = r.sensor2theta(i);
2817             if (theta > 180.0) {
2818                 theta -= 360.0;
2819             }
2820             turn_arb->vote(theta, AVOID_TURN_SIGMA, -wt);
2821         }
2822     }
2823 }
2824
2825 void agent::avoid_bias_left(void)
2826 {
2827     // If front is completely blocked, bias avoidance toward the left
2828     side
2829
2830     if (r.range.max(FWD_RT, FWD_LF) > AVOID_BIAS_DIST) {
2831         return;
2832     }
2833
2834     turn_arb->vote(AVOID_BIAS_ANGLE, AVOID_BIAS_SIGMA, AVOID_BIAS_WT);

```

```

2835 }
2836
2837 void agent::avoid_bias_right(void)
2838 {
2839     // If front is completely blocked, bias avoidance toward the right
2840     side
2841
2842     if (r.range.max(FWD_RT, FWD_LF) > AVOID_BIAS_DIST) {
2843         return;
2844     }
2845
2846     turn_arb->vote(-AVOID_BIAS_ANGLE, AVOID_BIAS_SIGMA, AVOID_BIAS_WT);
2847 }
2848
2849 void agent::follow_wall_right(void)
2850 {
2851     // Align with right wall
2852
2853     double fturn; // Follow turn
2854
2855     if ((r.range.min(BBR, FFR) > FOLLOW_MAX_ALIGN_DIST) ||
2856         (r.arc[ FWD] <= FOLLOW_STOP_DIST)) {
2857         return;
2858     }
2859
2860     // cout << "min(RT,FWD) = <" << r.range.max(RT,FWD) << ">";
2861
2862     if ((r.arc[ BACK_RT] != r.arc[ FWD_RT] ) && (r.arc[ FWD] >
2863 FOLLOW_ABORT)) {
2864         fturn = FOLLOW_TURN_FACTOR * (double) (r.arc[ BACK_RT] -
2865 r.arc[ FWD_RT] );
2866         turn_arb->vote(fturn, FOLLOW_TURN_SIGMA, FOLLOW_WT);
2867     }
2868     // cout << "" << endl;
2869 }
2870
2871 void agent::follow_wall_left(void)
2872 {
2873     // Align with right wall
2874
2875     double fturn; // Follow turn
2876
2877     if ((r.range.min(BBL, FFL) > FOLLOW_MAX_ALIGN_DIST) ||
2878         (r.arc[ FWD] <= FOLLOW_STOP_DIST)) {
2879         return;
2880     }
2881
2882     // cout << "min(LF,FWD) = <" << r.range.max(LF,FWD) << ">";
2883
2884     if ((r.arc[ BACK_LF] != r.arc[ FWD_LF] ) && (r.arc[ FWD] >
2885 FOLLOW_ABORT)) {
2886         fturn= -FOLLOW_TURN_FACTOR * (double) (r.arc[ BACK_LF] -
2887 r.arc[ FWD_LF] );
2888         turn_arb->vote(fturn, FOLLOW_TURN_SIGMA, FOLLOW_WT);
2889     }
2890     // cout << "" << endl;
2891 }
2892

```

```

2893 void agent::maintain_distance_right(void)
2894 {
2895     // Maintain desired distance from right wall
2896
2897     int right_min;           // Minimum right range reading
2898     double mdturn;          // Maintain distance turn
2899
2900     if ((r.range.min(BBR, FFR) > FOLLOW_MAX_ALIGN_DIST) ||
2901         (r.arc[FWD] <= FOLLOW_STOP_DIST)) {
2902         return;
2903     }
2904
2905     right_min = r.range.min(BACK, FWD);
2906
2907     if (right_min != DESIRED_DIST) {
2908         mdturn = MD_TURN_FACTOR * (double) (DESIRED_DIST - right_min);
2909         turn_arb->vote(mdturn, MD_TURN_SIGMA, MD_WT);
2910         cout << "right_min = <" << right_min << "> : turning <" <<
2911         cmd[TURN]
2912         << ">" << endl;
2913     }
2914 }
2915
2916 void agent::maintain_distance_left(void)
2917 {
2918     // Maintain desired distance from left wall
2919
2920     int left_min;
2921     double mdturn;          // Maintain distance turn
2922
2923     if ((r.range.min(BBL, FFL) > FOLLOW_MAX_ALIGN_DIST) ||
2924         (r.arc[FWD] <= FOLLOW_STOP_DIST)) {
2925         return;
2926     }
2927
2928     left_min = r.range.min(FWD, BACK);
2929
2930     if (left_min != DESIRED_DIST) {
2931         mdturn = -MD_TURN_FACTOR * (double) (DESIRED_DIST - left_min);
2932         turn_arb->vote(mdturn, MD_TURN_SIGMA, MD_WT);
2933         cout << "left_min = <" << left_min << "> : turning <" << cmd[TURN]
2934         << ">" << endl;
2935     }
2936 }
2937
2938 /***** NAVIGATION BEHAVIORS *****/
2939
2940 int agent::follow_path(void)
2941 {
2942     // Turn to follow path
2943
2944     // Returns 1 if outgoing place link is active, 0 otherwise
2945
2946     double path_angle;       // Angle for navigation
2947
2948     if (pnet.output_valid == 0) {
2949         cout << "I'm lost..." << endl;
2950         return(0);

```

```

2951     }
2952
2953     path_angle = angle_sgn_diff(pnet.output, (double) r.theta / 10.0);
2954     turn_arb->vote(path_angle, NAV_SIGMA, NAV_WT * pnet.conf);
2955
2956     return(1);
2957 }
2958
2959 int agent::detect_dest(int destin)
2960 {
2961     // Detect arrival at destination
2962
2963     if (pnet.windex == destin) {
2964         cout << "Arrived at destination." << endl;
2965         tk("Arrived at destination.");
2966         return(1);
2967     }
2968     else {
2969         return(0);
2970     }
2971 }
2972
2973 void agent::goal_orient(int gx, int gy)
2974 {
2975     // Turn toward goal (turn in place if deviation is too high)
2976
2977     double bearing;           // Bearing from robot to goal
2978     double goal_angle;        // Angle between heading and bearing
2979
2980     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
2981
2982     //      cout << "goal = (" << gx << ", " << gy << ") : current = (" <<
2983 r.x << ", "
2984 //          << r.y << ") : distance = "
2985 //          << hypot((double) (gy - r.y), (double) (gx - r.x)) / 10.0
2986 //          << " : bearing = " << bearing << endl;
2987
2988     goal_angle = angle_sgn_diff(bearing, (double) r.theta / 10.0);
2989     turn_arb->vote(goal_angle, GOAL_SIGMA, GOAL_WT);
2990
2991     //      cout << "heading = " << (double) r.theta / 10.0 << " :
2992 goal_angle = "
2993 //          << goal_angle << endl;
2994 }
2995
2996 /***** FILE ACCESS FUNCTIONS *****/
2997
2998 void agent::save_net(void)
2999 {
3000     // Save net in directory
3001
3002     char dirname[ STRLEN ];
3003
3004     cout << "Enter directory name ==> ";
3005     cin >> dirname;
3006
3007     pnet.save_all(dirname);
3008 }

```

```

3009
3010 void agent::load_net(void)
3011 {
3012     // Load net from directory
3013
3014     cout << "Enter directory name ==> ";
3015     cin >> apndir;
3016
3017     pnet.load_all(apndir);
3018     pnet.display();
3019 }
3020
3021 /***** LOCALIZATION FUNCTIONS *****/
3022
3023 double agent::compute_range_err(int image[ NUM_RANGE] , vector rinput)
3024 {
3025     // Compute difference between image and range input
3026
3027     double match_err;
3028     int err_sum = 0;
3029     int i;
3030
3031     // cout << "image/input:error = ";
3032
3033     for (i = 0; i < NUM_RANGE; i++) {
3034         err_sum += abs(image[ i] - rinput[ i] );
3035         // cout << image[ i] << "/" << rinput[ i] << ":" <<
3036         // abs(image[ i] - rinput[ i] ) << " ";
3037     }
3038     // cout << endl;
3039
3040     match_err = (double) err_sum / (double) (NUM_RANGE * MAX_RANGE);
3041     cout << "match error = " << match_err << endl;
3042
3043     return(match_err);
3044 }
3045
3046 /***** EVIDENCE GRID DISPLAY FUNCTIONS
3047 *****/
3048
3049 void agent::grid_display(window *win, // Window pointer
3050                          Map3D map) // Evidence grid
3051 {
3052     // Display evidence grid in X window
3053
3054     double xd, yd; // Display coords
3055     double xscale, yscale, zscale; // Cell dimensions (tenths of
3056 inches)
3057     int x, y, z; // Cell index
3058     int xsize, ysize, zsize; // Grid dimensions (# cells)
3059     int p; // Occupancy probability
3060
3061     win->clear_window();
3062
3063     xsize = map.msize[ 0] ;
3064     ysize = map.msize[ 1] ;
3065     zsize = map.msize[ 2] ;
3066

```



```

3067     xscale = (map.himv[ 0] - map.lomv[ 0] ) * 120.0 / (double) xsize;
3068     yscale = (map.himv[ 1] - map.lomv[ 1] ) * 120.0 / (double) ysize;
3069     zscale = (map.himv[ 2] - map.lomv[ 2] ) * 120.0 / (double) zsize;
3070
3071     // cout << "Displaying grid (" << xsize << " x " << ysize << " x " <<
3072     zsize
3073     // << ") : scale = (" << xscale << ", " << yscale << ", " << zscale
3074     << ")"
3075     // << endl;
3076
3077     z = (int) ((SONAR_HEIGHT + HEIGHT_OFFSET - map.lomv[ 2] ) /
3078     (map.himv[ 2] - map.lomv[ 2] ) * zsize);
3079
3080     for (y = 0; y < ysize; y++) {
3081         for (x = 0; x < xsize; x++) {
3082             p = map.mapm[ z * xsize * ysize + y * xsize + x ];
3083
3084             xd = ((double) (x + 0.5) * xscale + map.lomv[ 0] * 120.0);
3085             yd = ((double) (y + 0.5) * yscale + map.lomv[ 1] * 120.0);
3086
3087             if (p > 0) {
3088                 win->display_circle(xd, yd, xscale / 4.0);
3089             }
3090             else if (p == 0) {
3091                 win->display_point(xd, yd);
3092             }
3093
3094             /*         if (p >= GRID_POS_THRESH) {
3095                 win->display_circle(xd, yd, xscale / 4.0);
3096             }
3097             else if (p > GRID_NEG_THRESH) {
3098                 if (p > 0) {
3099                     win->set_color("blue");
3100                     win->display_point(xd, yd);
3101                     win->set_color("black");
3102                 }
3103                 else if (p < 0) {
3104                     win->set_color("red");
3105                     win->display_point(xd, yd);
3106                     win->set_color("black");
3107                 }
3108                 else {
3109                     win->display_point(xd, yd);
3110                 }
3111             } */
3112
3113         }
3114     }
3115
3116     win->draw_arc_buffer();
3117     win->flush();
3118 }
3119
3120 void agent::grid_display_global(Map3D map)          // Evidence grid
3121 {
3122     // Display global evidence grid in X window
3123
3124     double xd, yd;                                // Display coords

```

```

3125     double xscale, yscale, zscale;      // Cell dimensions (tenths of
3126 inches)
3127     int x, y, z;                        // Cell index
3128     int xsize, ysize, zsize;           // Grid dimensions (# cells)
3129     int p;                             // Occupancy probability
3130
3131     global_window->clear_window();
3132
3133     xsize = map.msize[ 0 ];
3134     ysize = map.msize[ 1 ];
3135     zsize = map.msize[ 2 ];
3136
3137     xscale = (map.himv[ 0 ] - map.lomv[ 0 ]) * 120.0 / (double) xsize;
3138     yscale = (map.himv[ 1 ] - map.lomv[ 1 ]) * 120.0 / (double) ysize;
3139     zscale = (map.himv[ 2 ] - map.lomv[ 2 ]) * 120.0 / (double) zsize;
3140
3141     cout << "Displaying grid (" << xsize << " x " << ysize << " x " <<
3142 zsize
3143     << " ) : scale = (" << xscale << ", " << yscale << ", " << zscale <<
3144 " )"
3145     << endl;
3146
3147     z = (int) ((SONAR_HEIGHT + HEIGHT_OFFSET - map.lomv[ 2 ]) /
3148 (map.himv[ 2 ] - map.lomv[ 2 ]) * zsize);
3149
3150     for (y = 0; y < ysize; y++) {
3151         for (x = 0; x < xsize; x++) {
3152             p = map.mapm[ z * xsize * ysize + y * xsize + x ];
3153
3154             xd = ((double) (x + 0.5) * xscale + map.lomv[ 0 ] * 120.0);
3155             yd = ((double) (y + 0.5) * yscale + map.lomv[ 1 ] * 120.0);
3156
3157             if (p > 0) {
3158                 global_window->display_circle(xd, yd, xscale / 4.0);
3159             }
3160             else if (p == 0) {
3161                 global_window->display_point(xd, yd);
3162             }
3163
3164             /*         if (p >= GRID_POS_THRESH) {
3165                 global_window->display_circle(xd, yd, xscale / 4.0);
3166             }
3167             else if (p > GRID_NEG_THRESH) {
3168                 if (p > 0) {
3169                     global_window->set_color("blue");
3170                     global_window->display_point(xd, yd);
3171                     global_window->set_color("black");
3172                 }
3173                 else if (p < 0) {
3174                     global_window->set_color("red");
3175                     global_window->display_point(xd, yd);
3176                     global_window->set_color("black");
3177                 }
3178             }
3179             else {
3180                 global_window->display_point(xd, yd);
3181             }
3182             */

```

```

3183     }
3184 }
3185
3186 global_window->draw_arc_buffer();
3187 global_window->flush();
3188
3189 global_refresh = 1;
3190 }
3191
3192 void agent::display_place_grid(void)
3193 {
3194     // Display local grid for place
3195
3196     int index;           // Place index
3197
3198     if (pnet.num_units == 0) {
3199         cout << "No places in APN." << endl;
3200         return;
3201     }
3202
3203     cout << "Enter place index [ 0.." << pnet.num_units - 1 << "]" ==> " ";
3204     cin >> index;
3205
3206     if ((index < 0) || (index >= pnet.num_units)) {
3207         cout << "Nonexistent place." << endl;
3208         return;
3209     }
3210
3211     grid_display(grid_window, pnet.unit[index].lgrid);
3212 }
3213
3214 void agent::grid_display_edges(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] )
3215     // Colored grid
3216 {
3217     // Display edge segments detected in evidence grid
3218
3219     double xd, yd;           // Display coords
3220     double xscale, yscale;   // Cell dimensions (tenths of
3221                               // inches)
3222     int x, y;                // Cell index
3223     int xsize, ysize;        // Grid dimensions (# cells)
3224     int p;                   // Occupancy probability
3225
3226     xsize = GLOBAL_X_RES;
3227     ysize = GLOBAL_Y_RES;
3228
3229     xscale = (GLOBAL_X_MAX - GLOBAL_X_MIN) * 120.0 / (double) xsize;
3230     yscale = (GLOBAL_Y_MAX - GLOBAL_Y_MIN) * 120.0 / (double) ysize;
3231
3232     // cout << "Displaying grid (" << xsize << " x " << ysize << " x " <<
3233     // zsize
3234     // << " ) : scale = (" << xscale << ", " << yscale << ", " << zscale
3235     // << ")"
3236     // << endl;
3237
3238     global_window->set_color(EDGE_COLOR);
3239
3240

```

```

3241     for (y = 0; y < ysize; y++) {
3242         for (x = 0; x < xsize; x++) {
3243             p = grid[x][y];
3244
3245             xd = (double) (x + 0.5) * xscale + GLOBAL_X_MIN * 120.0;
3246             yd = (double) (y + 0.5) * yscale + GLOBAL_Y_MIN * 120.0;
3247
3248             if (p > 0) {
3249                 global_window->display_circle(xd, yd, xscale / 4.0);
3250             }
3251         }
3252     }
3253
3254     global_window->set_color("black");
3255
3256     global_window->draw_arc_buffer();
3257     global_window->flush();
3258 }
3259
3260 void agent::grid_display_regions(int grid[ GLOBAL_X_RES][ GLOBAL_Y_RES] )
3261     // Colored grid
3262 {
3263     // Display regions detected in evidence grid
3264
3265     double xd, yd;           // Display coords
3266     double xscale, yscale;   // Cell dimensions (tenths of
3267     inches)
3268     int x, y;                // Cell index
3269     int xsize, ysize;        // Grid dimensions (# cells)
3270     int p;                   // Occupancy probability
3271
3272     xsize = GLOBAL_X_RES;
3273     ysize = GLOBAL_Y_RES;
3274
3275     xscale = (GLOBAL_X_MAX - GLOBAL_X_MIN) * 120.0 / (double) xsize;
3276     yscale = (GLOBAL_Y_MAX - GLOBAL_Y_MIN) * 120.0 / (double) ysize;
3277
3278     // cout << "Displaying grid (" << xsize << " x " << ysize << " x " <<
3279     zsize
3280     << ") : scale = (" << xscale << ", " << yscale << ", " << zscale
3281     << ")"
3282     // << endl;
3283
3284     for (x = 0; x < xsize; x++) {
3285         for (y = 0; y < ysize; y++) {
3286             p = grid[x][y];
3287
3288             xd = (double) (x + 0.5) * xscale + GLOBAL_X_MIN * 120.0;
3289             yd = (double) (y + 0.5) * yscale + GLOBAL_Y_MIN * 120.0;
3290
3291             if (p > 0) {
3292                 global_window->set_color(color_table[ (grid[x][y] - 1) %
3293                 DISPLAY_COLORS] );
3294                 // cout << "display color = "
3295                 // << color_table[ (grid[x][y] - 1) % DISPLAY_COLORS] <<
3296                 endl;
3297                 global_window->display_circle(xd, yd, xscale / 4.0);
3298             }
3299         }
3300     }

```

```

3299     global_window->set_color("black");
3300 }
3301 }
3302 }
3303
3304 global_window->draw_arc_buffer();
3305 global_window->flush();
3306 }
3307
3308 void agent::display_robot(window *win,      // Window
3309                          int x, int y,    // Robot position (1/10 inch)
3310                          int theta,      // Robot heading (1/10 degree)
3311                          int turret)     // Robot turret angle (1/10 degree)
3312 {
3313     // Display robot in window
3314
3315     // Local constants
3316
3317     const double robot_rad = ROBOT_RADIUS * 120.0; // Robot radius (1/10
3318 inch)
3319     const double half_rad = robot_rad * 0.5;      // Half radius (1/10
3320 inch)
3321     const double tendeg = 0.1 * DEG2RAD;          // 1/10 degree in
3322 radians
3323
3324     static double old_fx, old_fy;                // Old robot position
3325     static double old_ftheta;                    // Old robot heading
3326     static double old_fturret;                   // Old robot turret angle
3327     static double old_bx, old_by;                // Old endpoint of base line
3328     static double old_tx1, old_ty1,              // Old endpoints of turret line
3329         old_tx2, old_ty2;
3330
3331     double fx, fy;                               // Robot position (floating point)
3332     double ftheta;                               // Robot heading (floating point)
3333     double fturret;                              // Robot turret angle (floating point)
3334     double bx, by;                               // Endpoint of base line
3335     double tx1, ty1, tx2, ty2;                  // Endpoints of turret line
3336
3337     fx = (double) x;
3338     fy = (double) y;
3339     ftheta = (double) theta;
3340     fturret = (double) turret;
3341
3342     bx = fx + cos(ftheta * tendeg) * half_rad;
3343     by = fy + sin(ftheta * tendeg) * half_rad;
3344
3345     tx1 = fx + cos(fturret * tendeg) * half_rad;
3346     ty1 = fy + sin(fturret * tendeg) * half_rad;
3347
3348     tx2 = fx + cos(fturret * tendeg) * robot_rad;
3349     ty2 = fy + sin(fturret * tendeg) * robot_rad;
3350
3351     if (!global_refresh) {
3352         win->display_xor_circle(old_fx, old_fy, robot_rad);
3353         win->display_xor_line(old_fx, old_fy, old_bx, old_by);
3354         win->display_xor_line(old_tx1, old_ty1, old_tx2, old_ty2);
3355     }
3356     global_refresh = 0;

```



```

3357
3358 win->display_xor_circle(fx, fy, robot_rad);
3359 win->display_xor_line(fx, fy, bx, by);
3360 win->display_xor_line(tx1, ty1, tx2, ty2);
3361
3362 win->flush();
3363
3364 old_fx = fx;
3365 old_fy = fy;
3366 old_ftheta = ftheta;
3367 old_fturret = fturret;
3368
3369 old_bx = bx;
3370 old_by = by;
3371
3372 old_tx1 = tx1;
3373 old_ty1 = ty1;
3374 old_tx2 = tx2;
3375 old_ty2 = ty2;
3376 }
3377
3378 /***** FRONTIER FUNCTIONS *****/
3379
3380 void agent::frontier_copy(frontier &f1, frontier f2)
3381 {
3382     // Copy frontier <f2> to frontier <f1>
3383
3384     f1.x = f2.x;
3385     f1.y = f2.y;
3386     f1.size = f2.size;
3387     f1.color = f2.color;
3388 }
3389
3390 void agent::find_frontiers(void)
3391 {
3392     // Find frontiers in global grid
3393
3394     find_frontier_edges(&global_grid, &edge_grid, SONAR_HEIGHT);
3395     find_frontier_regions(edge_grid, SONAR_HEIGHT);
3396     // grid_display_global(global_grid);
3397     grid_display_regions(region_map);
3398     display_region_centroids(0.0, 0.0);
3399     // display_robot_region_centroids();
3400 }
3401
3402 void agent::find_frontier_edges(Map3D *raw,          // Raw evidence grid
3403 (pointer)
3404                               Map3D *edge,          // Frontier edge grid
3405 (pointer)
3406                               double height)         // Z-coord of edge plane
3407 {
3408     // Find frontier edges in <raw> grid and store them in <edge> grid
3409
3410     int xsize, ysize, zsize;    // Grid dimensions (# cells)
3411     int x, y, z;                // Cell index
3412     int p;                      // Occupancy probability
3413     int unk;                    // Unknown neighbor flag (0 = true)
3414

```

```

3415     xsize = raw->msize[ 0] ;
3416     ysize = raw->msize[ 1] ;
3417     zsize = raw->msize[ 2] ;
3418
3419     if ((xsize != edge->msize[ 0]) || (ysize != edge->msize[ 1]) ||
3420         (zsize != edge->msize[ 2])) {
3421         cout << "find_frontier_edges: Grid size mismatch." << endl;
3422         return;
3423     }
3424
3425     z = (int) ((height + HEIGHT_OFFSET - raw->lomv[ 2]) /
3426               (raw->himv[ 2] - raw->lomv[ 2]) * zsize);
3427
3428     for (x = 1; x < xsize - 1; x++) {
3429         for (y = 1; y < ysize - 1; y++) {
3430             edge->mapm[ z * xsize * ysize + y * xsize + x] = 0;
3431
3432             p = raw->mapm[ z * xsize * ysize + y * xsize + x];
3433
3434             if (p < 0) {
3435
3436                 // unk = 0 if and only if one of cell (x,y)'s neighbors is unknown
3437
3438                 unk = raw->mapm[ z * xsize * ysize + y * xsize + x - 1] *
3439                     raw->mapm[ z * xsize * ysize + y * xsize + x + 1] *
3440                     raw->mapm[ z * xsize * ysize + (y - 1) * xsize + x] *
3441                     raw->mapm[ z * xsize * ysize + (y + 1) * xsize + x];
3442
3443                 if (unk == 0) {
3444                     edge->mapm[ z * xsize * ysize + y * xsize + x] = 1;
3445                 }
3446             }
3447
3448             /*         if (p <= GRID_NEG_THRESH) {
3449             if (((raw->mapm[ z * xsize * ysize + y * xsize + x - 1]
3450                  > GRID_NEG_THRESH) &&
3451                  (raw->mapm[ z * xsize * ysize + y * xsize + x - 1]
3452                   < GRID_POS_THRESH)) ||
3453                  ((raw->mapm[ z * xsize * ysize + y * xsize + x + 1]
3454                   > GRID_NEG_THRESH) &&
3455                  (raw->mapm[ z * xsize * ysize + y * xsize + x + 1]
3456                   < GRID_POS_THRESH)) ||
3457                  ((raw->mapm[ z * xsize * ysize + (y - 1) * xsize + x]
3458                   > GRID_NEG_THRESH) &&
3459                  (raw->mapm[ z * xsize * ysize + (y - 1) * xsize + x]
3460                   < GRID_POS_THRESH)) ||
3461                  ((raw->mapm[ z * xsize * ysize + (y + 1) * xsize + x]
3462                   > GRID_NEG_THRESH) &&
3463                  (raw->mapm[ z * xsize * ysize + (y + 1) * xsize + x]
3464                   < GRID_POS_THRESH))) {
3465                 edge->mapm[ z * xsize * ysize + y * xsize + x] = 1;
3466             }
3467             */
3468         }
3469     }
3470 }
3471 }
3472

```

```

3473 void agent::find_frontier_regions(Map3D edge,           // Frontier edge
3474 grid
3475                                double height) // Z-coord of edge plane
3476 {
3477     // Find frontier regions in <edge> grid and add new frontiers
3478
3479     spread_segment(edge, region_map, height);
3480     analyze_regions(region_map);
3481 }
3482
3483 void agent::spread_segment(Map3D grid,           // Uncolored grid
3484 int color[ GLOBAL_X_RES][ GLOBAL_Y_RES] ,
3485                                // Colored grid
3486                                double height) // Z-coord of edge plane
3487 {
3488     // Segment <grid> image into regions in <color> using spreading
3489     activation
3490
3491     int x, y, z;           // Cell index
3492     int nx, ny;           // Neighboring cell index
3493     int num_colors = 1;    // Number of colors
3494     int xsize, ysize, zsize; // Grid dimensions (# cells)
3495     int changed;           // Flag indicating whether cell colors
3496     changed
3497
3498     // Find grid dimensions
3499
3500     xsize = grid.msize[ 0] ;
3501     ysize = grid.msize[ 1] ;
3502     zsize = grid.msize[ 2] ;
3503
3504     z = (int) ((height + HEIGHT_OFFSET - grid.lomv[ 2] ) /
3505                (grid.himv[ 2] - grid.lomv[ 2] ) * zsize);
3506
3507     // Set initial colors
3508
3509     for (x = 0; x < xsize; x++) {
3510         for (y = 0; y < ysize; y++) {
3511             if (grid.mapm[ z * xsize * ysize + y * xsize + x] == 0) {
3512                 color[ x][ y] = 0;
3513             }
3514             else {
3515                 color[ x][ y] = num_colors;
3516                 num_colors++;
3517             }
3518         }
3519     }
3520
3521     // Use spreading activation to segment regions
3522
3523     do {
3524         changed = 0;
3525         for (x = 0; x < xsize; x++) {
3526             for (y = 0; y < ysize; y++) {
3527                 for (nx = x - 1; nx <= x + 1; nx++) {
3528                     for (ny = y - 1; ny <= y + 1; ny++) {
3529                         if ((nx >= 0) && (nx < GLOBAL_X_RES) &&
3530                             (ny >= 0) && (ny < GLOBAL_Y_RES)) {

```

```

3531         if ((color[nx][ny] > 0) && (color[nx][ny] < color[x][y])) {
3532             color[x][y] = color[nx][ny];
3533             changed = 1;
3534         }
3535     }
3536 }
3537 }
3538 }
3539 }
3540 }
3541 while(changed);
3542 }
3543
3544 void agent::print_region_map(int grid[GLOBAL_X_RES][GLOBAL_Y_RES])
3545     // Colored grid
3546 {
3547     // Print colored grid cell values
3548
3549     char symbol;           // Cell symbol
3550     int x, y;              // Cell index
3551
3552     cout << endl;
3553     for (x = 0; x < GLOBAL_X_RES; x++) {
3554         for (y = 0; y < GLOBAL_Y_RES; y++) {
3555             if (grid[x][y] == 0) {
3556                 cout << ".";
3557             }
3558             else {
3559                 if (grid[x][y] < 10) {
3560                     symbol = '0' + (char) grid[x][y];
3561                 }
3562                 else if (grid[x][y] < 36) {
3563                     symbol = 'A' + (char) (grid[x][y] - 10);
3564                 }
3565                 else {
3566                     symbol = 'a' + (char) (grid[x][y] - 36);
3567                 }
3568                 cout << symbol;
3569             }
3570         }
3571         cout << endl;
3572     }
3573     cout << endl;
3574 }
3575
3576 void agent::analyze_regions(int grid[GLOBAL_X_RES][GLOBAL_Y_RES])
3577     // Colored grid
3578 {
3579     // Determine size and centroid of frontier regions
3580
3581     double xscale, yscale;           // Cell dimensions (tenths of
3582     inches)
3583     double cx, cy;                   // Centroid of new region
3584     int count[MAX_COLORS];           // Edge cell counter for regions
3585     int x_sum[MAX_COLORS];           // Sum of cell x-coords
3586     int y_sum[MAX_COLORS];           // Sum of cell y-coords
3587     int x, y;                         // Cell index
3588     int i;

```

```

3589
3590     num_front = 0;
3591
3592     xscale = (GLOBAL_X_MAX - GLOBAL_X_MIN) * 120.0 / (double)
3593     GLOBAL_X_RES;
3594     yscale = (GLOBAL_Y_MAX - GLOBAL_Y_MIN) * 120.0 / (double)
3595     GLOBAL_Y_RES;
3596
3597     for (i = 0; i < MAX_COLORS; i++) {
3598         count[i] = 0;
3599         x_sum[i] = 0;
3600         y_sum[i] = 0;
3601     }
3602
3603     for (x = 0; x < GLOBAL_X_RES; x++) {
3604         for (y = 0; y < GLOBAL_Y_RES; y++) {
3605             if (grid[x][y] > 0) {
3606                 count[grid[x][y]]++;
3607                 x_sum[grid[x][y]] += x;
3608                 y_sum[grid[x][y]] += y;
3609             }
3610         }
3611     }
3612
3613     for (i = 1; i < MAX_COLORS; i++) {
3614         if (count[i] >= MIN_REGION_SIZE) {
3615             cx =
3616             xscale * (double) x_sum[i] / (double) count[i] + GLOBAL_X_MIN *
3617             120.0;
3618             cy =
3619             yscale * (double) y_sum[i] / (double) count[i] + GLOBAL_Y_MIN *
3620             120.0;
3621
3622             if (!(visited(cx, cy) || inaccessible(cx, cy))) {
3623                 // if (!inaccessible(cx, cy)) {
3624                 if (num_front == MAX_FRONTIERS) {
3625                     cout << "analyze_regions: Too many regions (>" << MAX_FRONTIERS
3626                     << ")." << endl;
3627                 }
3628                 else {
3629                     frontiers[num_front].color = i;
3630                     frontiers[num_front].size = count[i];
3631                     frontiers[num_front].x = cx;
3632                     frontiers[num_front].y = cy;
3633                     num_front++;
3634                 }
3635             }
3636         }
3637     }
3638
3639     for (i = 0; i < num_front; i++) {
3640         cout << "Region [" << i << "] : size = " << frontiers[i].size
3641         << " : centroid = (" << frontiers[i].x << ", " << frontiers[i].y
3642         << ")" << endl;
3643     }
3644 }
3645
3646 int agent::visited(double cx, double cy) // Centroid of new region

```



```

3647 {
3648     // Check whether centroid corresponds to previously visited frontier
3649     // Return 1 if visited, 0 otherwise
3650
3651     double dist;           // Distance from new region to visited frontier
3652     int i;
3653
3654     // cout << "Checking (" << cx << ", " << cy << ") against visited
3655     list."
3656     //      << endl;
3657
3658     for (i = 0; i < num_visit; i++) {
3659         dist = hypot(cx - front_visit[i].x, cy - front_visit[i].y);
3660         //      cout << "front_visit[" << i << "] at (" << front_visit[i].x <<
3661         ", "
3662         //      << front_visit[i].y << ") : distance = " << dist;
3663         if (dist <= VISIT_RADIUS) {
3664             //      cout << " [- VISITED -]" << endl;
3665             return(1);
3666         }
3667         //      cout << endl;
3668     }
3669
3670     return(0);
3671 }
3672
3673 int agent::inaccessible(double cx, double cy) // Centroid of new
3674 region
3675 {
3676     // Check whether centroid corresponds to inaccessible frontier
3677     // Return 1 if inaccessible, 0 otherwise
3678
3679     double dist;           // Distance from new region to inaccessible
3680     frontier
3681     int i;
3682
3683     // cout << "Checking (" << cx << ", " << cy << ") against
3684     inaccessible list."
3685     //      << endl;
3686
3687     for (i = 0; i < num_inac; i++) {
3688         dist = hypot(cx - front_inac[i].x, cy - front_inac[i].y);
3689         //      cout << "front_inac[" << i << "] at (" << front_inac[i].x <<
3690         ", "
3691         //      << front_inac[i].y << ") : distance = " << dist;
3692         if (dist <= INAC_RADIUS) {
3693             //      cout << " [* INACCESSIBLE *]" << endl;
3694             return(1);
3695         }
3696         //      cout << endl;
3697     }
3698
3699     return(0);
3700 }
3701
3702 int agent::closest_frontier(double x, double y)
3703 {
3704     // Return index of unvisited, accessible frontier closest to (x, y)

```

```

3705 // Return -1 if no such frontier exists
3706
3707 double min_dist = MAX_DIST; // Minimum distance to frontier
3708 double dist = -1;           // Distance to frontier
3709 int close_index = -1;        // Index of closest frontier
3710 int i;
3711
3712 for (i = 0; i < num_front; i++) {
3713     if (!(visited(frontiers[i].x, frontiers[i].y) ||
3714         inaccessible(frontiers[i].x, frontiers[i].y))) {
3715         // if (!inaccessible(frontiers[i].x, frontiers[i].y)) {
3716         dist = hypot(x - frontiers[i].x, y - frontiers[i].y);
3717         if (dist < min_dist) {
3718             min_dist = dist;
3719             close_index = i;
3720         }
3721     }
3722 }
3723
3724 return(close_index);
3725 }
3726
3727 void agent::display_region_centroids(double cx, // Display center x-
3728 coord
3729                                     double cy) // Display center y-coord
3730 {
3731     // Mark region centroids in evidence grid window
3732
3733     double xd, yd; // Display coords
3734     char label[ STRLEN ]; // Mark label (index)
3735     int mark_color; // Mark color
3736     int i;
3737
3738     for (i = 0; i < num_front; i++) {
3739         xd = frontiers[i].x - cx;
3740         yd = frontiers[i].y - cy;
3741
3742         mark_color = (frontiers[i].color - 1) % DISPLAY_COLORS;
3743         // cout << "Drawing frontier [" << i << "]" in " <<
3744 color_table[mark_color]
3745         // << " (" << mark_color << ")" << endl;
3746
3747         global_window->set_color(color_table[mark_color]);
3748         global_window->display_circle(xd, yd, CENTROID_MARK_RADIUS);
3749         global_window->display_line(xd - CENTROID_MARK_RADIUS, yd,
3750             xd + CENTROID_MARK_RADIUS, yd);
3751         global_window->display_line(xd, yd - CENTROID_MARK_RADIUS,
3752             xd, yd + CENTROID_MARK_RADIUS);
3753
3754         sprintf(label, "%d", i);
3755         global_window->display_text(xd + CENTROID_MARK_RADIUS * 2.0, yd,
3756 label);
3757         global_window->set_color("black");
3758     }
3759     global_window->flush();
3760     // cout << endl;
3761
3762     // for (i = 0; i < DISPLAY_COLORS; i++) {

```

```

3763 // global_window->set_color(color_table[i]);
3764 // global_window->display_line(0, i * -100, 1000, i * -100);
3765 // }
3766 // global_window->set_color("black");
3767 // global_window->flush();
3768 }
3769
3770 void agent::display_robot_region_centroids(void)
3771 {
3772 // Mark region centroids in robot window
3773
3774 int xd, yd; // Display coords
3775 int mark_color; // Mark color
3776 int color_mode; // Color mode for draw command
3777 int i;
3778
3779 refresh_all();
3780
3781 for (i = 0; i < num_front; i++) {
3782 xd = (int) frontiers[i].x;
3783 yd = (int) frontiers[i].y;
3784
3785 // mark_color = (frontiers[i].color - 1) % DISPLAY_COLORS;
3786 // color_mode = robot_color[mark_color] + 2;
3787 // cout << "Drawing frontier [" << i << "]" in " <<
3788 color_table[mark_color]
3789 // << " (" << robot_color[mark_color] << ") [mode " <<
3790 color_mode << "]"
3791 // << endl;
3792
3793 color_mode = 1;
3794
3795 draw_arc(xd - (int) CENTROID_MARK_RADIUS, yd + (int)
3796 CENTROID_MARK_RADIUS,
3797 (int) (CENTROID_MARK_RADIUS * 2.0),
3798 (int) (CENTROID_MARK_RADIUS * 2.0),
3799 0, 3600, color_mode);
3800 draw_line(xd - (int) CENTROID_MARK_RADIUS, yd,
3801 xd + (int) CENTROID_MARK_RADIUS, yd, color_mode);
3802 draw_line(xd, yd - (int) CENTROID_MARK_RADIUS,
3803 xd, yd + (int) CENTROID_MARK_RADIUS, color_mode);
3804 }
3805 // cout << endl;
3806
3807 // for (i = 0; i < DISPLAY_COLORS; i++) {
3808 // color_mode = robot_color[i] + 2;
3809 // draw_line(0, i * -100, 1000, i * -100, color_mode);
3810 // }
3811 }
3812
3813 int agent::check_frontier_cell(int x, int y, // Cell index
3814 int front_index) // Frontier index
3815 {
3816 // Check whether cell (x, y) is part of frontier <front_index>
3817
3818 if (frontiers[front_index].color == region_map[x][y]) {
3819 return(1);
3820 }

```

```

3821     else {
3822         return(0);
3823     }
3824 }
3825
3826 /***** NAVIGATION FUNCTIONS *****/
3827
3828 void agent::corridor_advance(void)
3829 {
3830     // Move forward if front corridor is clear
3831
3832     if (wide_corridor[FWD] == 1) {
3833         // TEMP FIX for SCOUT comment out mv command below and change to
3834         scout_vm
3835         // mv(MV_VM, CORRIDOR_SPEED_WIDE, MV_IGNORE, 0, MV_IGNORE, 0);
3836         cout << "In corridor_advance wide_corridor about to call scout_vm ("
3837             << CORRIDOR_SPEED_WIDE << ", 0" << endl; // TEMP FIX for SCOUT
3838         scout_vm(CORRIDOR_SPEED_WIDE, 0); // TEMP FIX for SCOUT
3839     }
3840     else if (corridor[FWD] == 1) {
3841         // TEMP FIX for SCOUT comment out mv command below and change to
3842         scout_vm
3843         // mv(MV_VM, CORRIDOR_SPEED, MV_IGNORE, 0, MV_IGNORE, 0);
3844         cout << "In corridor_advance corridor about to call scout_vm ("
3845             << CORRIDOR_SPEED << ", 0" << endl; // TEMP FIX for SCOUT
3846         scout_vm(CORRIDOR_SPEED, 0); // TEMP FIX for SCOUT
3847     }
3848     else {
3849         // TEMP FIX for SCOUT comment out mv command below and change to
3850         scout_vm
3851         // mv(MV_VM, 0, MV_IGNORE, 0, MV_IGNORE, 0);
3852         cout << "In corridor_advance else about to call scout_vm (0,0" << endl;
3853         // TEMP FIX for SCOUT
3854         scout_vm(0, 0); // TEMP FIX for SCOUT
3855     }
3856 }
3857
3858 void agent::goal_corridor_orient(int gx, int gy)
3859 {
3860     // Turn toward clear corridor closest to goal bearing
3861
3862     double bearing;           // Bearing from robot to goal
3863     double corridor_index;    // Index of selected corridor (-1 = none)
3864     double corridor_bearing;  // Bearing of selected corridor
3865     double cmd_bearing;       // Bearing to face
3866
3867     update();
3868
3869     bearing = atan2((double) (gy - r.y), (double) (gx - r.x)) * RAD2DEG;
3870
3871     // cout << "goal = (" << gx << ", " << gy << ") : current = (" <<
3872     r.x << ", "
3873     // << r.y << ") : distance = "
3874     // << hypot((double) (gy - r.y), (double) (gx - r.x)) / 10.0
3875     // << " : bearing = " << bearing << endl;
3876
3877     detect_corridors();
3878     corridor_index = select_corridor(bearing);

```

```

3879     corridor_bearing =
3880         angle_wrap((double) (corridor_index * SENSOR_SEP + r.theta) /
3881 10.0);
3882
3883     if ((corridor_index == -1) ||
3884         (angle_diff(bearing, corridor_bearing) > CORRIDOR_MAX_DEVIATION))
3885     {
3886         cmd_bearing =
3887             angle_wrap((double) r.theta / 10.0 +
3888                 rrand(-GOAL_CORRIDOR_NOISE, GOAL_CORRIDOR_NOISE));
3889     }
3890     else {
3891         cmd_bearing =
3892             angle_wrap(corridor_bearing +
3893                 rrand(-GOAL_CORRIDOR_NOISE, GOAL_CORRIDOR_NOISE));
3894     }
3895
3896     //     cout << "corridor index = " << corridor_index << " : corridor
3897 bearing = "
3898         //         << corridor_bearing << " : command bearing = " <<
3899 cmd_bearing << endl;
3900
3901     r.face_angle_fast((int) (cmd_bearing * 10.0)); // TEMP FIX for
3902 SCOUT
3903 }
3904
3905 void agent::update_nav_grid(void)
3906 {
3907     // Update navigation grid based on global grid
3908
3909     // grid_fine_to_coarse(global_grid, nav_grid);
3910
3911     grid_copy(nav_grid, global_grid);
3912
3913     // grid_display(nav_window, nav_grid);
3914 }
3915
3916 int agent::path_plan(double wx, double wy, // World coords of goal
3917                     path &nav_path) // Navigation path (optimized)
3918 {
3919     // Plan path to goal location (return 1 if path found, 0 otherwise)
3920
3921     path rev_path; // Reversed path
3922     path unopt_path; // Unoptimized navigation path
3923     path opt_path; // Optimized navigation path
3924     int gx, gy, gz; // Grid coordinates of destination
3925     int rx, ry, rz; // Grid coordinates of robot
3926     int x, y; // Cell index
3927     int search_status; // Flag indicating whether path has been found
3928
3929     world2grid(nav_grid, (double) r.x / 120.0, (double) r.y / 120.0,
3930 0, &rx, &ry, &rz);
3931
3932     world2grid(nav_grid, wx / 120.0, wy / 120.0, 0, &gx, &gy, &gz);
3933
3934     cout << "Robot location = (" << r.x << ", " << r.y << ") [" << rx <<
3935 ", "
3936         << ry << "]" << endl;

```



```

3937 cout << "Goal location = (" << wx << ", " << wy << ") [" << gx << ", "
3938 << gy << "]" << endl;
3939
3940 update_nav_grid();
3941
3942 for (x = 0; x < NAV_X_RES; x++) {
3943     for (y = 0; y < NAV_Y_RES; y++) {
3944         visit[x][y] = 0;
3945     }
3946 }
3947
3948 search_status = find_path(rx, ry, gx, gy, rev_path);
3949
3950 if (search_status == SEARCH_FAIL) {
3951     cout << "No path found." << endl;
3952     return(0);
3953 }
3954
3955 reverse_path(rev_path, unopt_path);
3956
3957 cout << "Unoptimized: ";
3958 print_path(unopt_path);
3959
3960 optimize_path(unopt_path, opt_path);
3961 cout << "Optimized: ";
3962 print_path(opt_path);
3963
3964 generate_world_path(opt_path, nav_path);
3965 cout << "World path:";
3966 print_path(nav_path);
3967
3968 // grid_display(nav_window, nav_grid);
3969 // display_path(nav_path, OPT_PATH_COLOR, nav_window);
3970 display_path(nav_path, OPT_PATH_COLOR, global_window);
3971 // display_path_robot(nav_path, ROBOT_OPT_PATH_COLOR);
3972
3973 return(1);
3974 }
3975
3976 int agent::frontier_path_plan(double wx, double wy, // World coords of
3977 goal
3978             int front_index, // Frontier index
3979             path &nav_path) // Navigation path
3980 {
3981     // Plan path to goal location (return 1 if path found, 0 otherwise)
3982
3983     path rev_path; // Reversed path
3984     path unopt_path; // Unoptimized navigation path
3985     path opt_path; // Optimized navigation path
3986     int gx, gy, gz; // Grid coordinates of destination
3987     int rx, ry, rz; // Grid coordinates of robot
3988     int x, y; // Cell index
3989     int search_status; // Flag indicating whether path has been found
3990
3991     world2grid(nav_grid, (double) r.x / 120.0, (double) r.y / 120.0,
3992                0, &rx, &ry, &rz);
3993
3994     world2grid(nav_grid, wx / 120.0, wy / 120.0, 0, &gx, &gy, &gz);

```

```

3995
3996     cout << "Robot location = (" << r.x << ", " << r.y << ") [" << rx <<
3997     ", "
3998         << ry << "]" << endl;
3999     cout << "Goal location = (" << wx << ", " << wy << ") [" << gx << ", "
4000         << gy << "]" << endl;
4001
4002     update_nav_grid();
4003
4004     for (x = 0; x < NAV_X_RES; x++) {
4005         for (y = 0; y < NAV_Y_RES; y++) {
4006             visit[x][y] = 0;
4007         }
4008     }
4009
4010     search_status = frontier_find_path(rx, ry, gx, gy, front_index,
4011     rev_path);
4012
4013     if ((search_status == SEARCH_FAIL) || (search_status ==
4014     SEARCH_TIMEOUT)) {
4015         cout << "No path found." << endl;
4016         return(0);
4017     }
4018
4019     reverse_path(rev_path, unopt_path);
4020
4021     cout << "Unoptimized: ";
4022     print_path(unopt_path);
4023
4024     optimize_path(unopt_path, opt_path);
4025     cout << "Optimized: ";
4026     print_path(opt_path);
4027
4028     generate_world_path(opt_path, nav_path);
4029     cout << "World path:";
4030     print_path(nav_path);
4031
4032     // grid display(nav_window, nav_grid);
4033     // display_path(nav_path, OPT_PATH_COLOR, nav_window);
4034     display_path(nav_path, OPT_PATH_COLOR, global_window);
4035     // display_path_robot(nav_path, ROBOT_OPT_PATH_COLOR);
4036
4037     return(1);
4038 }
4039
4040 void agent::print_path(path p)
4041 {
4042     // Print all cells on path
4043
4044     int i;
4045
4046     cout << "path length = " << p.length << " : path = ";
4047
4048     for (i = 0; i < p.length; i++) {
4049         cout << "(" << p.x[i] << ", " << p.y[i] << ") ";
4050     }
4051
4052     cout << endl;

```

```

4053 }
4054
4055 void agent::display_path(path p,           // Path
4056                          char *pcolor,     // Path color
4057                          window *win)      // Window
4058 {
4059     // Draw path in window
4060
4061     int i;
4062
4063     win->set_color(pcolor);
4064
4065     for (i = 0; i < p.length - 1; i++) {
4066         win->display_line(p.x[i], p.y[i], p.x[i + 1], p.y[i + 1]);
4067     }
4068
4069     win->flush();
4070     win->set_color("black");
4071 }
4072
4073 void agent::display_path_robot(path p,           // Path
4074                                int pcolor)       // Path color
4075 {
4076     // Draw path in robot window
4077
4078     int i;
4079
4080     for (i = 0; i < p.length - 1; i++) {
4081         draw_line(p.x[i], p.y[i], p.x[i + 1], p.y[i + 1], pcolor + 2);
4082     }
4083 }
4084
4085 int agent::find_path(int sx, int sy,           // Start cell
4086                     int gx, int gy,         // Goal cell
4087                     path &p)                // Path
4088 {
4089     // Find path from (sx, sy) to (gx, gy)
4090
4091     int nx, ny;           // Neighbor cell index
4092
4093     path_init(p);
4094
4095     visit[sx][sy] = 1;
4096
4097     while(closest_neighbor(sx, sy, gx, gy, nx, ny)) {
4098         if (search_cell(nx, ny, gx, gy, p) == SEARCH_SUCCESS) {
4099             // cout << "[ ON PATH (" << x << ", " << y << ") ]" << endl;
4100             path_add(p, sx, sy);
4101             return(SEARCH_SUCCESS);
4102         }
4103     }
4104
4105     return(SEARCH_FAIL);
4106 }
4107
4108 int agent::frontier_find_path(int sx, int sy, // Start cell
4109                               int gx, int gy, // Goal cell
4110                               int front_index, // Frontier index

```

```

4111         path &p)           // Path
4112     {
4113         // Find path from (sx, sy) to (gx, gy) or any point on frontier
4114         <front_index>
4115
4116         int nx, ny;           // Neighbor cell index
4117         int status;           // Cell search status
4118
4119         path_init(p);
4120
4121         visit[ sx][ sy] = 1;
4122
4123         while(closest_neighbor(sx, sy, gx, gy, nx, ny)) {
4124             cell_count = 0;
4125             status = frontier_search_cell(nx, ny, gx, gy, front_index, p);
4126             if (status == SEARCH_SUCCESS) {
4127                 //      cout << "[ ON PATH (" << x << ", " << y << ") ]" << endl;
4128                 path_add(p, sx, sy);
4129                 return(SEARCH_SUCCESS);
4130             }
4131             if (status == SEARCH_TIMEOUT) {
4132                 return(SEARCH_TIMEOUT);
4133             }
4134         }
4135
4136         return(SEARCH_FAIL);
4137     }
4138
4139     int agent::search_cell(int x, int y,           // Search cell
4140                           int gx, int gy,         // Goal cell
4141                           path &p)                // Path
4142     {
4143         // Search cell (x,y) and return search status
4144
4145         int status;           // Search status
4146         int nx, ny;           // Neighbor cell index
4147
4148         if (visit[ x][ y] ) {
4149             cout << "search_cell: Error: revisited cell (" << x << ", " << y <<
4150             ")"
4151                 << endl;
4152             exit(-1);
4153         }
4154         visit[ x][ y] = 1;
4155
4156         //      cout << "Searching (" << x << ", " << y << ") : ";
4157
4158         if ((x < 0) || (x >= NAV_X_RES) || (y < 0) || (y >= NAV_Y_RES)) {
4159             //      cout << "Out of bounds." << endl;
4160             return(SEARCH_FAIL);
4161         }
4162
4163
4164         if ((x == gx) && (y == gy)) {
4165             //      cout << "[ * GOAL (" << x << ", " << y << ") *]" << endl;
4166             path_add(p, x, y);
4167             return(SEARCH_SUCCESS);
4168         }

```

```

4169
4170 if ((nav_grid.mapm[ grid2index(nav_grid, x, y, 0)] >= 0) ||
4171      (!check_clear(x, y))) {
4172     //      cout << "> BLOCKED <" << endl;
4173     return(SEARCH_FAIL);
4174 }
4175
4176 //      cout << "(( Searching adjacent ))" << endl;
4177
4178 while(closest_neighbor(x, y, gx, gy, nx, ny)) {
4179     if (search_cell(nx, ny, gx, gy, p) == SEARCH_SUCCESS) {
4180         //      cout << "[ ON PATH (" << x << ", " << y << ") ]" << endl;
4181         path_add(p, x, y);
4182         return(SEARCH_SUCCESS);
4183     }
4184 }
4185
4186 return(SEARCH_FAIL);
4187 }
4188
4189 int agent::frontier_search_cell(int x, int y,          // Search cell
4190                                int gx, int gy,        // Goal cell
4191                                int front_index,       // Frontier index
4192                                path &p)              // Path
4193 {
4194     // Search cell (x,y) while navigating to frontier and return search
4195     status
4196
4197     int child_status;          // Search status for child cell
4198     int nx, ny;               // Neighbor cell index
4199
4200     cell_count++;
4201     if (cell_count % 100 == 0) {
4202         cout << "Searching " << cell_count << " cells..." << endl;
4203     }
4204     if (cell_count > SEARCH_MAX_CELLS) {
4205         cell_count = 0;
4206         return(SEARCH_TIMEOUT);
4207     }
4208
4209     if (visit[x][y]) {
4210         cout << "frontier_search_cell: Error: revisited cell (" << x << ", "
4211 << y << ")"
4212         << endl;
4213         exit(-1);
4214     }
4215     visit[x][y] = 1;
4216
4217     //      cout << "Searching (" << x << ", " << y << ") : ";
4218
4219     if ((x < 0) || (x >= NAV_X_RES) || (y < 0) || (y >= NAV_Y_RES)) {
4220         //      cout << "Out of bounds." << endl;
4221
4222         return(SEARCH_FAIL);
4223     }
4224
4225
4226     //      if ((x == gx) && (y == gy)) {

```



```

4227
4228 if ((x == gx) && (y == gy)) ||
4229     (check_frontier_arrival(x, y, front_index))) {
4230     // cout << "[ * GOAL (" << x << ", " << y << ") *]" << endl;
4231     path_add(p, x, y);
4232     return(SEARCH_SUCCESS);
4233 }
4234
4235 if ((nav_grid.mapm[ grid2index(nav_grid, x, y, 0)] >= 0) ||
4236     (!check_clear(x, y))) {
4237     // cout << "> BLOCKED <" << endl;
4238     return(SEARCH_FAIL);
4239 }
4240
4241 // cout << "(( Searching adjacent ))" << endl;
4242
4243 while(closest_neighbor(x, y, gx, gy, nx, ny)) {
4244     child_status = frontier_search_cell(nx, ny, gx, gy, front_index, p);
4245     if (child_status == SEARCH_SUCCESS) {
4246         // cout << "[ ON PATH (" << x << ", " << y << ") ]" << endl;
4247         path_add(p, x, y);
4248         return(SEARCH_SUCCESS);
4249     }
4250     if (child_status == SEARCH_TIMEOUT) {
4251         return(SEARCH_TIMEOUT);
4252     }
4253 }
4254
4255 return(SEARCH_FAIL);
4256 }
4257
4258 int agent::closest_neighbor(int x, int y,          // Current cell index
4259                             int gx, int gy,       // Goal cell index
4260                             int &nx, int &ny)     // Next cell index
4261 {
4262     // Find index of (unvisited) neighbor closest to goal
4263
4264     double min_dist;          // Minimum distance from neighbor to goal
4265     double dist;              // Distance from neighbor to goal
4266     int found = 0;            // 1 if unvisited neighbor exists, 0 otherwise
4267     int dx, dy;               // Adjacent cell offset
4268     int ax, ay;               // Adjacent cell index
4269
4270     min_dist = (double) MAX_PATH_LENGTH;
4271
4272     for (dx = -1; dx <= 1; dx++) {
4273         for (dy = -1; dy <= 1; dy++) {
4274             ax = x + dx;
4275             ay = y + dy;
4276
4277             if ((ax >= 0) && (ax < NAV_X_RES) && (ay >= 0) && (ay <
4278 NAV_Y_RES)) {
4279                 if (visit[ax][ay] == 0) {
4280                     dist = hypot(gx - ax, gy - ay);
4281                     if (dist < min_dist) {
4282                         min_dist = dist;
4283                         nx = ax;
4284                         ny = ay;

```

```

4285         found = 1;
4286     }
4287 }
4288 }
4289 }
4290 }
4291
4292     return(found);
4293 }
4294
4295 void agent::reverse_path(path old_path,          // Initial path
4296                          path &new_path) // Reversed path
4297 {
4298     // Reverse order of steps on path
4299
4300     int i;
4301
4302     path_init(new_path);
4303     for (i = 0; i < old_path.length; i++) {
4304         path_add(new_path, old_path.x[ (old_path.length - 1) - i],
4305                  old_path.y[ (old_path.length - 1) - i]);
4306     }
4307 }
4308
4309 void agent::optimize_path(path old_path, // Initial path
4310                           path &new_path) // Optimized path
4311 {
4312     // Optimize path by jumping between adjacent path cells
4313
4314     int marker = 0; // Point along old path
4315     int jump_marker; // Point to jump to on new path
4316     int jump_flag; // Set to 1 if path jumps
4317
4318     path_init(new_path);
4319     path_add(new_path, old_path.x[ 0], old_path.y[ 0]);
4320
4321     // cout << "Starting at (" << new_path.x[ 0] << ", " << new_path.y[ 0]
4322     //      << ") [ 0] <0>" << endl;
4323
4324     while(marker < old_path.length - 1) {
4325         jump_flag = 0;
4326         // cout << "Trying to jump from (" << new_path.x[ new_path.length
4327 - 1] << ", "
4328         //      << new_path.y[ new_path.length - 1] << ") [" <<
4329 new_path.length - 1
4330         //      << "]" << " << marker << ">" << endl;
4331         for (jump_marker = old_path.length - 1;
4332              (jump_marker > marker) && !jump_flag;
4333              jump_marker--) {
4334             // cout << "Checking (" << old_path.x[ jump_marker] << ", "
4335             //      << old_path.y[ jump_marker] << ") << " << jump_marker << ">"
4336 << endl;
4337             if ((old_path.x[ jump_marker] - old_path.x[ marker] >= -1) &&
4338                 (old_path.x[ jump_marker] - old_path.x[ marker] <= 1) &&
4339                 (old_path.y[ jump_marker] - old_path.y[ marker] >= -1) &&
4340                 (old_path.y[ jump_marker] - old_path.y[ marker] <= 1)) {

```

```

4342     path_add(new_path, old_path.x[ jump_marker] ,
4343     old_path.y[ jump_marker] );
4344     //      cout << "Jumping from (" << new_path.x[ new_path.length - 2]
4345     << ", "
4346     //      << new_path.y[ new_path.length - 2] << ") to ("
4347     //      << new_path.x[ new_path.length - 1] << ", "
4348     //      << new_path.y[ new_path.length - 1] << ")" << endl;
4349
4350     marker = jump_marker;
4351     jump_flag = 1;
4352 }
4353 }
4354 }
4355 }
4356
4357 void agent::generate_world_path(path grid_path,          // Path in nav
4358 grid
4359                               path &world_path) // Path in world coords
4360 {
4361     // Convert path in grid cell coords to world coords
4362
4363     double wx, wy;          // World coords
4364     double xscale, yscale, zscale;    // Cell dimensions (tenths of
4365 inches)
4366     int xsize, ysize, zsize;          // Grid dimensions (# cells)
4367     int i;
4368
4369     xsize = nav_grid.msize[ 0] ;
4370     ysize = nav_grid.msize[ 1] ;
4371     zsize = nav_grid.msize[ 2] ;
4372
4373     xscale = (nav_grid.himv[ 0] - nav_grid.lomv[ 0] ) * 120.0 / (double)
4374 xsize;
4375     yscale = (nav_grid.himv[ 1] - nav_grid.lomv[ 1] ) * 120.0 / (double)
4376 ysize;
4377     zscale = (nav_grid.himv[ 2] - nav_grid.lomv[ 2] ) * 120.0 / (double)
4378 zsize;
4379
4380     path_init(world_path);
4381
4382     for (i = 0; i < grid_path.length; i++) {
4383         wx = (((double) grid_path.x[ i] + 0.5) * xscale
4384             + nav_grid.lomv[ 0] * 120.0);
4385         wy = (((double) grid_path.y[ i] + 0.5) * yscale
4386             + nav_grid.lomv[ 1] * 120.0);
4387
4388         path_add(world_path, (int) wx, (int) wy);
4389     }
4390 }
4391
4392 void agent::path_init(path &p)          // Path
4393 {
4394     // Initialize path
4395
4396     p.length = 0;
4397 }
4398
4399 void agent::path_add(path &p, // Path

```

```

4400         int x, int y)          // Point to add to path
4401     {
4402         // Add point to path
4403
4404         if (p.length == MAX_PATH_LENGTH) {
4405             cout << "path_add: Too many steps (> " << MAX_PATH_LENGTH << ")." <<
4406             endl;
4407             exit(-1);
4408         }
4409
4410         p.x[p.length] = x;
4411         p.y[p.length] = y;
4412         p.length++;
4413     }
4414
4415     int agent::check_clear(int x, int y)
4416     {
4417         // Check to see whether region around point is free of known
4418         obstacles
4419
4420         int obs_count = 0;          // Obstacle counter
4421         int xi, yi;                // Grid indices
4422         int xl, xh, yl, yh, zl, zh; // Grid coords of robot-sized box around
4423         point
4424         double wx, wy, wz;          // World coordinates of point
4425         double wxl, wxh, wyl, wyh; // World coords of robot-sized box around
4426         point
4427
4428         // int xsize, ysize;        // Grid dimensions (# cells)
4429         // double xscale, yscale;    // Cell dimensions (tenths of inches)
4430         // double xd, yd;            // Display coords
4431
4432         grid2world(nav_grid, x, y, 0, &wx, &wy, &wz);
4433
4434         wxl = wx - ROBOT_PASSAGE_RADIUS;
4435         wxh = wx + ROBOT_PASSAGE_RADIUS;
4436         wyl = wy - ROBOT_PASSAGE_RADIUS;
4437         wyh = wy + ROBOT_PASSAGE_RADIUS;
4438
4439         world2grid(nav_grid, wxl, wyl, wz, &xl, &yl, &zl);
4440         world2grid(nav_grid, wxh, wyh, wz, &xh, &yh, &zh);
4441
4442         // xsize = NAV_X_RES;
4443         // ysize = NAV_Y_RES;
4444
4445         // xscale = (NAV_X_MAX - NAV_X_MIN) * 120.0 / (double) xsize;
4446         // yscale = (NAV_Y_MAX - NAV_Y_MIN) * 120.0 / (double) ysize;
4447
4448         for (xi = xl; xi <= xh; xi++) {
4449             for (yi = yl; yi <= yh; yi++) {
4450                 // xd = (double) (xi + 0.5) * xscale + GLOBAL_X_MIN * 120.0;
4451                 // yd = (double) (yi + 0.5) * yscale + GLOBAL_Y_MIN * 120.0;
4452
4453                 // global_window->set_color("gold");
4454                 // global_window->display_point(xd, yd);
4455                 // global_window->set_color("black");
4456
4457                 if (nav_grid.mapm[ grid2index(nav_grid, xi, yi, 0)] > 0) {

```

```

4458         //      global_window->set_color("red");
4459         //      global_window->display_circle(xd, yd, xscale);
4460         //      global_window->set_color("black");
4461         obs_count++;
4462     }
4463 }
4464 }
4465
4466     if (obs_count > MAX_OBS_COUNT) {
4467         return(0);
4468     }
4469     else {
4470         return(1);
4471     }
4472 }
4473
4474 int agent::check_frontier_arrival(int x, int y, int front_index)
4475 {
4476     // Check to see whether region around point overlaps frontier
4477
4478     int xi, yi;                // Grid indices
4479     int xl, xh, yl, yh, zl, zh; // Grid coords of robot-sized box around
4480 point
4481     double wx, wy, wz;         // World coordinates of point
4482     double wxl, wxh, wyl, wyh; // World coords of robot-sized box around
4483 point
4484
4485     grid2world(nav_grid, x, y, 0, &wx, &wy, &wz);
4486
4487     wxl = wx - ROBOT_PASSAGE_RADIUS;
4488     wxh = wx + ROBOT_PASSAGE_RADIUS;
4489     wyl = wy - ROBOT_PASSAGE_RADIUS;
4490     wyh = wy + ROBOT_PASSAGE_RADIUS;
4491
4492     world2grid(nav_grid, wxl, wyl, wz, &xl, &yl, &zl);
4493     world2grid(nav_grid, wxh, wyh, wz, &xh, &yh, &zh);
4494
4495     for (xi = xl; xi <= xh; xi++) {
4496         for (yi = yl; yi <= yh; yi++) {
4497             if (check_frontier_cell(xi, yi, front_index)) {
4498                 return(1);
4499             }
4500         }
4501     }
4502     return(0);
4503 }
4504
4505 double agent::closest_waypoint(path p,                // Path
4506                                int x, int y,          // Current position (1/10
4507 inch)
4508                                int index, // Index of current waypoint
4509                                int &close_index) // Index of closest waypoint
4510 {
4511     // Finds waypoint furthest on path within destination tolerance, or
4512     // waypoint on path <p> closest to (x, y), returning the distance
4513 (inches)
4514     // to that point, and the waypoint's index in <index>
4515

```



```

4516 double dist; // Distance to waypoint
4517 double min_dist = MAX_DIST; // Minimum distance to waypoint
4518 int last_waypoint; // Last waypoint to check
4519 int i;
4520
4521 // cout << "current position = (" << x << ", " << y << ")" << endl;
4522
4523 if ((index < 0) || (index >= p.length)) {
4524     cout << "closest_waypoint: index <" << index << "> out of range
4525 [ 0.."
4526     << p.length << "]" << endl;
4527     exit(-1);
4528 }
4529
4530 // Set lookahead window for checking waypoints
4531
4532 last_waypoint = index + WAYPOINT_WINDOW;
4533 if (last_waypoint > p.length - 1) {
4534     last_waypoint = p.length - 1;
4535 }
4536
4537 // Search for closest waypoint
4538
4539 for (i = last_waypoint; i >= index; i--) {
4540     dist = hypot((double) (p.x[i] - x), (double) (p.y[i] - y)) / 10.0;
4541
4542     // cout << "distance to waypoint [" << i << "] (" << p.x[i] << ",
4543 "
4544     // << p.y[i] << ") = " << dist << endl;
4545
4546     if (dist < min_dist) {
4547         min_dist = dist;
4548         close_index = i;
4549
4550         if (min_dist <= LOCAL_NAV_TOLERANCE) {
4551             cout << "[* ARRIVED *]" << endl;
4552             return(min_dist);
4553         }
4554     }
4555 }
4556
4557 // cout << "closest waypoint [" << close_index << "] (" <<
4558 p.x[close_index]
4559 // << " , " << p.y[close_index] << ") : dist = " << min_dist <<
4560 endl;
4561
4562 return(min_dist);
4563 }
4564
4565
4566 /***** CORRIDOR FUNCTIONS *****/
4567
4568 void agent::detect_corridors(void)
4569 {
4570     // Detect freespace corridors in vicinity of robot
4571
4572     int i;
4573

```

```

4574     update();
4575
4576     for (i = 0; i < NUM_RANGE; i++) {
4577         corridor[i] = check_corridor(i, CORRIDOR_FWD_RANGE,
4578                                     CORRIDOR_SIDE_CLEARANCE);
4579         wide_corridor[i] = check_corridor(i, CORRIDOR_WIDE_FWD_RANGE,
4580                                         CORRIDOR_WIDE_SIDE_CLEARANCE);
4581     }
4582
4583     // display_corridors();
4584     // global_window->flush();
4585
4586     // display_corridors();
4587 }
4588
4589
4590 int agent::check_corridor(int center,      // Index of sensor in center
4591                          of_corridor
4592                          int fwd_range,   // Required forward space
4593                          int side_clear) // Required side space
4594 {
4595     // Check whether a corridor exists centered around sensor <center>
4596     // Return 1 if true, 0 otherwise
4597
4598     int sensor;          // Sensor index
4599     int start;           // First sensor to be checked
4600     int end;             // Last sensor to be checked
4601
4602     // cout << "Checking corridor [" << center << "]" << endl;  // TEMP FIX
4603     for SCOUT
4604
4605         start = wrap(center - CORRIDOR_SPAN, 0, NUM_RANGE - 1);
4606         end = wrap(center + CORRIDOR_SPAN, 0, NUM_RANGE - 1);
4607
4608         if (start < end) {
4609             for (sensor = start; sensor <= end; sensor++) {
4610                 if (!corridor_check_sensor(center, sensor, fwd_range, side_clear))
4611                 {
4612                     // cout << "Corridor [" << center << "]" is >> BLOCKED << "." << endl;  //
4613                     TEMP FIX for SCOUT
4614                     return(0);
4615                 }
4616             }
4617             // cout << "Corridor [" << center << "]" is [[ OPEN ]].< << endl;  //
4618             TEMP FIX for SCOUT
4619             return(1);
4620         }
4621
4622         for (sensor = start; sensor < NUM_RANGE; sensor++) {
4623             if (!corridor_check_sensor(center, sensor, fwd_range, side_clear)) {
4624                 // cout << "Corridor [" << center << "]" is >> BLOCKED << "." << endl;  //
4625                 TEMP FIX for SCOUT
4626                 return(0);
4627             }
4628         }
4629
4630         for (sensor = 0; sensor <= end; sensor++) {
4631             if (!corridor_check_sensor(center, sensor, fwd_range, side_clear)) {

```

```

4632 // cout << "Corridor [" << center << "]" is >> BLOCKED << "." << endl; //
4633 TEMP FIX for SCOUT
4634     return(0);
4635 }
4636 }
4637 // cout << "Corridor [" << center << "]" is [[ OPEN ]]. " << endl; //
4638 TEMP FIX for SCOUT
4639     return(1);
4640 }
4641
4642 int agent::corridor_check_sensor(int center,          // Center sensor
4643 index
4644                                     int sensor,          // Sensor index
4645                                     int fwd_range,        // Required fwd space
4646                                     int side_clear) // Required side space
4647 {
4648     // Check whether <sensor> is clear for corridor <center>
4649
4650     const double bot_width = ROBOT_RADIUS * 12.0; // Robot width (inches)
4651     const double sens_sep = SENSOR_SEP * 0.1;     // Sensor separation
4652     (degrees)
4653
4654     double angle;          // Sensor angle (degrees)
4655     double center_angle;   // Angle of center sensor (degrees)
4656     double theta;          // Angle (degrees) between sensor and
4657                             // perpendicular to center angle
4658     double thresh;         // Minimum clear distance (inches)
4659
4660     center_angle = angle_wrap((double) r.theta * 0.1
4661                               + (double) center * sens_sep);
4662     // TEMP FIX for SCOUT - changed r.turret to r.theta on previous line
4663     // cout << "center [" << center << "]" : center angle = " << center_angle
4664     << endl; // TEMP FIX for SCOUT
4665
4666     angle = angle_wrap((double) r.theta * 0.1 + (double) sensor *
4667 sens_sep); // TEMP FIX for SCOUT r.turret to r.theta
4668     theta = 90.0 - angle_diff(center_angle, angle);
4669
4670     if (center == sensor) {
4671         thresh = fwd_range;
4672     }
4673     else {
4674         thresh = (bot_width + side_clear) / cos(theta * DEG2RAD)
4675                 - bot_width;
4676         if (thresh > fwd_range) {
4677             thresh = fwd_range;
4678         }
4679     }
4680
4681     // cout << "sensor [" << sensor << "]" : sensor angle = " << angle
4682     //          << " : theta = " << theta << " : thresh = " << thresh
4683     //          << " : range = " << r.range[sensor]; // TEMP FIX for SCOUT
4684
4685     if (r.range[sensor] < thresh) {
4686         // cout << " * BLOCKED * " << endl; // TEMP FIX for SCOUT
4687         return(0);
4688     }
4689     else {

```

```

4690 // cout << " [ CLEAR ]" << endl; // TEMP FIX for SCOUT
4691 return(1);
4692 }
4693 }
4694
4695 void agent::display_corridors(void)
4696 {
4697     // Display corridors in robot window
4698
4699     int i;
4700
4701     // refresh_all();
4702
4703     for (i = 0; i < NUM_RANGE; i++) {
4704         if (wide_corridor[i] == 1) {
4705             display_corridor(global_window, i, CORRIDOR_WIDE_FWD_RANGE,
4706                             CORRIDOR_WIDE_SIDE_CLEARANCE, CORRIDOR_WIDE_COLOR);
4707             // display_corridor_robot(i, CORRIDOR_WIDE_FWD_RANGE,
4708                                     CORRIDOR_WIDE_SIDE_CLEARANCE,
4709                                     CORRIDOR_WIDE_COLOR_ROBOT);
4710         }
4711         else if (corridor[i] == 1) {
4712             display_corridor(global_window, i, CORRIDOR_FWD_RANGE,
4713                             CORRIDOR_SIDE_CLEARANCE, CORRIDOR_COLOR);
4714             // display_corridor_robot(i, CORRIDOR_FWD_RANGE,
4715                                     CORRIDOR_SIDE_CLEARANCE,
4716                                     CORRIDOR_COLOR_ROBOT);
4717         }
4718     }
4719 }
4720
4721 void agent::display_corridor(window *win, // Window
4722                             int center, // Center sensor index
4723                             int fwd_range, // Required forward space
4724                             int side_clear, // Required side space
4725                             char *color) // Corridor color
4726 {
4727     // Display corridor boundaries centered around sensor <center>
4728
4729     // Robot width (1/10 inch)
4730     const double bot_width = ROBOT_RADIUS * 120.0;
4731
4732     double fwd_dist; // Length of forward axis (1/10 inch)
4733     double side_dist; // Distance to either side of robot (1/10 inch)
4734     double angle; // Corridor angle (degrees)
4735     double x1, y1, x2, y2, x3, y3, x4, y4; // Corner coords (1/10 inch)
4736     double fwd_x, fwd_y; // Offset for forward end
4737
4738     fwd_dist = bot_width + (double) fwd_range * 10.0;
4739     side_dist = bot_width + (double) side_clear * 10.0;
4740
4741     // SCOUT THESIS CHANGE - changed r.turret to r.theta in line below
4742     angle = angle_wrap((double) r.theta * 0.1
4743                       + (double) (center * SENSOR_SEP) * 0.1);
4744
4745     x1 = r.x + side_dist * cos((angle + 90.0) * DEG2RAD);
4746     y1 = r.y + side_dist * sin((angle + 90.0) * DEG2RAD);
4747

```

```

4748     x2 = r.x + side_dist * cos((angle - 90.0) * DEG2RAD);
4749     y2 = r.y + side_dist * sin((angle - 90.0) * DEG2RAD);
4750
4751     fwd_x = fwd_dist * cos(angle * DEG2RAD);
4752     fwd_y = fwd_dist * sin(angle * DEG2RAD);
4753
4754     x3 = x1 + fwd_x;
4755     y3 = y1 + fwd_y;
4756
4757     x4 = x2 + fwd_x;
4758     y4 = y2 + fwd_y;
4759
4760     win->set_color(color);
4761
4762     win->display_line(x1, y1, x2, y2);
4763     win->display_line(x2, y2, x4, y4);
4764     win->display_line(x4, y4, x3, y3);
4765     win->display_line(x3, y3, x1, y1);
4766
4767     win->set_color("black");
4768 }
4769
4770 void agent::display_corridor_robot(int center, // Center sensor index
4771                                   int fwd_range, // Required forward space
4772                                   int side_clear, // Required side space
4773                                   int color) // Corridor color
4774 {
4775     // Display corridor boundaries centered around sensor <center> in
4776     robot window
4777
4778     // Robot width (1/10 inch)
4779     const double bot_width = ROBOT_RADIUS * 120.0;
4780
4781     double fwd_dist; // Length of forward axis (1/10 inch)
4782     double side_dist; // Distance to either side of robot (1/10 inch)
4783     double angle; // Corridor angle (degrees)
4784     double x1, y1, x2, y2, x3, y3, x4, y4; // Corner coords (1/10 inch)
4785     double fwd_x, fwd_y; // Offset for forward end
4786
4787     fwd_dist = bot_width + (double) fwd_range * 10.0;
4788     side_dist = bot_width + (double) side_clear * 10.0;
4789
4790     // SCOUT THESIS CHANGE - changed r.turret to r.theta in line below
4791     angle = angle_wrap((double) r.theta * 0.1
4792                       + (double) (center * SENSOR_SEP) * 0.1);
4793
4794     x1 = r.x + side_dist * cos((angle + 90.0) * DEG2RAD);
4795     y1 = r.y + side_dist * sin((angle + 90.0) * DEG2RAD);
4796
4797     x2 = r.x + side_dist * cos((angle - 90.0) * DEG2RAD);
4798     y2 = r.y + side_dist * sin((angle - 90.0) * DEG2RAD);
4799
4800     fwd_x = fwd_dist * cos(angle * DEG2RAD);
4801     fwd_y = fwd_dist * sin(angle * DEG2RAD);
4802
4803     x3 = x1 + fwd_x;
4804     y3 = y1 + fwd_y;
4805

```



```

4806     x4 = x2 + fwd_x;
4807     y4 = y2 + fwd_y;
4808
4809     draw_line((int) x1, (int) y1, (int) x2, (int) y2, color + 2);
4810     draw_line((int) x2, (int) y2, (int) x4, (int) y4, color + 2);
4811     draw_line((int) x4, (int) y4, (int) x3, (int) y3, color + 2);
4812     draw_line((int) x3, (int) y3, (int) x1, (int) y1, color + 2);
4813 }
4814
4815 int agent::select_corridor(double heading)        // Heading (degrees)
4816 {
4817     // Select corridor nearest to specified heading
4818
4819     const double sens_sep = SENSOR_SEP * 0.1;    // Sensor separation
4820     (degrees)
4821     double angle;                                // Sensor angle
4822     double dtheta;                                // Angle/heading deviation
4823     double min_dtheta = 360.0;                    // Minimum angle deviation
4824     int select = -1;                               // Index of selected corridor
4825     int i;
4826
4827     heading = angle_wrap(heading);
4828
4829     for (i = 0; i < NUM_RANGE; i++) {
4830         if (corridor[i] == 1) {
4831             angle = angle_wrap((double) r.theta * 0.1
4832                               + (double) i * sens_sep);
4833             // SCOUT THESIS CHANGE - use r.theta vice r.turret in line above
4834             // TEMP FIX for SCOUT - lets try some numbers checking below
4835             // cout << "About to call angle_diff with heading= " << heading
4836             // << "and angle = " << angle << endl;    // TEMP FIX for SCOUT
4837             dtheta = angle_diff(heading, angle);
4838             // cout << "dtheta = angle_diff(heading,angle) = " << dtheta << endl;
4839             // TEMP FIX for SCOUT
4840             // cout << "min_dtheta = " << min_dtheta << "   i = " << i << endl;    //
4841             TEMP FIX for SCOUT
4842             if (dtheta < min_dtheta) {
4843                 min_dtheta = dtheta;
4844                 select = i;
4845             }
4846         }
4847     }
4848
4849     if (select == -1) {
4850         cout << "No open corridors." << endl;
4851         return(select);
4852     }
4853     //SCOUT THESIS CHANGE - changed r.turret to r.theta 3 lines down
4854     cout << "desired heading = " << heading << " : selected corridor ["
4855           << select << "]" : corridor angle = "
4856           << angle_wrap((double) r.theta * 0.1 + (double) select *
4857     sens_sep)
4858           << " : deviation = " << min_dtheta << endl;
4859
4860     if (wide_corridor[select] == 1) {
4861         // display_corridor(global_window, select,
4862         CORRIDOR_WIDE_FWD_RANGE,

```

```

4863         //          CORRIDOR_WIDE_SIDE_CLEARANCE,
4864 CORRIDOR_SELECT_WIDE_COLOR);
4865         //      display_corridor_robot(select, CORRIDOR_WIDE_FWD_RANGE,
4866         //          CORRIDOR_WIDE_SIDE_CLEARANCE,
4867         //          CORRIDOR_SELECT_WIDE_COLOR_ROBOT);
4868     }
4869     else {
4870         //      display_corridor(global_window, select, CORRIDOR_FWD_RANGE,
4871         //          CORRIDOR_SIDE_CLEARANCE, CORRIDOR_SELECT_COLOR);
4872         //      display_corridor_robot(select, CORRIDOR_FWD_RANGE,
4873 CORRIDOR_SIDE_CLEARANCE,
4874         //          CORRIDOR_SELECT_COLOR_ROBOT);
4875     }
4876
4877     return(select);
4878 }
4879
4880 /***** INTERFACE TO CONTINUOUS LOCALIZATION *****/
4881
4882 void agent::connect_cl(void)
4883 {
4884     // Initialize communications with continuous localization
4885
4886     char comm_mach[ STRLEN] ;
4887
4888     cout << "Enter continuous localization host ==> ";
4889     cin >> comm_mach;
4890     cin.get();
4891
4892     // connect_to_CL(CONTLOC_CHANNEL, CONTLOC_HOST);
4893     // cout << "Connected to CONTINUOUS LOCALIZATION on " << CONTLOC_HOST
4894 << "."
4895     //      << endl;
4896
4897     connect_to_CL(CONTLOC_CHANNEL, comm_mach);
4898     cout << "Connected to CONTINUOUS LOCALIZATION on " << comm_mach << "."
4899         << endl;
4900
4901     contloc_mode = 1;
4902 }
4903
4904 void agent::send_cl_grid(void)
4905 {
4906     // Send global grid to continuous localization
4907
4908     if (!contloc_mode) {
4909         return;
4910     }
4911
4912     cout << "Sending global grid to CONTINUOUS LOCALIZATION." << endl;
4913     save_grid_file(global_grid, ARIEL_CL_FILE, "");
4914
4915     // SCOUT THESIS CHANGE - if continuous localization is ever used send
4916     r.theta instead of r.turret
4917     sendroom_to_CL(CONTLOC_CHANNEL, ARIEL_CL_FILE, (double) r.x / 10.0,
4918         (double) r.y / 10.0, (double) r.theta / 10.0,
4919         (double) r.theta / 10.0, 0, 0.0, 0.0, 0.0);
4920 }

```

```

4921
4922 /***** MULTIROBOT COMMUNICATION *****/
4923
4924 // BEGIN SCOUT THESIS CHANGE
4925 // This routine now sets up communication for up to MAX_ROBOTS
4926 simultaneously
4927 // 2 robot limitation is eliminated
4928
4929 void agent::init_robot_comm(void)
4930 {
4931     // Initialize robot communication channel
4932
4933     char robot_server_name [ STRLEN]; // Server robot host name
4934
4935     // If Server Robot
4936     if (r.id == SERVER_ROBOT) {
4937         if (init_comm_server(ARIEL_CHANNEL, PORT_ARIEL, NONBLOCK_COMM) == 0)
4938         {
4939             cout << "init_robot_comm: Robot [" << r.id
4940                 << "]" initialized communications as server." << endl;
4941             multi_mode = 1;
4942         }
4943         else {
4944             cout << "init_robot_comm: Robot [" << r.id
4945                 << "]" unable to set up communications as server." << endl;
4946             multi_mode = 0;
4947         }
4948     }
4949     else if (r.id <= MAX_ROBOTS) {
4950         cout << "Enter host name for server robot ==> ";
4951         cin >> robot_server_name;
4952
4953         if (init_comm_client(ARIEL_CHANNEL, robot_server_name,
4954             BASE_CLIENT_PORT + r.id, NONBLOCK_COMM) == 0) {
4955             cout << "init_robot_comm: Robot [" << r.id
4956                 << "]" initialized communications as client." << endl;
4957             multi_mode = 1;
4958         }
4959         else {
4960             cout << "init_robot_comm: Robot [" << r.id
4961                 << "]" unable to set up communications as client." << endl;
4962             multi_mode = 0;
4963         }
4964     }
4965     else {
4966         cout << "init_robot_comm: Robot [" << r.id
4967             << "]" unable to set up communications for more than "
4968             << MAX_ROBOTS
4969             << " robots." << endl;
4970         multi_mode = 0;
4971     }
4972 }
4973 //END SCOUT THESIS CHANGE
4974
4975 void agent::send_robot_message(char *message)
4976 {
4977     // Send message to other robot
4978     // BEGIN SCOUT THESIS CHANGE

```

```

4979     cout << "Sending message <" << message << ">." << endl;
4980     // Loop thru all possible client robots connections, send message
4981     // that new map is available.
4982     for (int i=1; i< MAX_ROBOTS; i++){
4983         write_comm(i, message, strlen(message) + 1);
4984     }
4985 //END SCOUT THESIS CHANGE
4986 }
4987
4988 void agent::user_send_robot_message(void)
4989 {
4990     // Send message to other robot (user mode)
4991
4992     char message[ STRLEN] ;
4993
4994     cout << "Enter message ==> ";
4995     cin >> message;
4996
4997     cout << "Sending message <" << message << ">." << endl;
4998
4999     write_comm(ARIEL_CHANNEL, message, strlen(message) + 1);
5000 }
5001
5002 //BEGIN SCOUT THESIS CHANGE
5003 // Pass in the channel used for communication between client
5004 // and server
5005
5006 int agent::receive_robot_message(int channel, char *message)
5007 {
5008     // Receive message from other robot
5009     // Returns 1 if message received, 0 otherwise
5010
5011     int message_received;          // Message receipt flag
5012
5013     message_received = read_comm(channel, message, STRLEN);
5014 // END SCOUT THESIS CHANGE
5015     if (message_received) {
5016         cout << "Received message <" << message << ">." << endl;
5017     }
5018
5019     return(message_received);
5020 }
5021
5022 void agent::user_receive_robot_message(void)
5023 {
5024     // Receive message from other robot (user mode)
5025
5026     char message[ STRLEN] ;
5027
5028     if (read_comm(ARIEL_CHANNEL, message, STRLEN) == 0) {
5029         cout << "No messages waiting." << endl;
5030     }
5031     else {
5032         cout << "Received message <" << message << ">." << endl;
5033     }
5034 }
5035
5036 /***** MULTIROBOT EXPLORATION *****/

```

```

5037
5038 void agent::integrate_remote_map(void)
5039 {
5040     // Integrate new map from remote robot (if a new map exists)
5041
5042     Map3D remote_grid;           // Evidence grid for remote map
5043     char mapfile[ STRLEN];       // Remote map file
5044     char posinfo[ STRLEN];       // Remote map position information
5045     int mx, my, mtheta;          // Position of center of new map
5046                                 // (1/10 inch, 1/10 degree)
5047 // BEGIN SCOUT THESIS CHANGE
5048     int channel;                 // Channel number
5049
5050     // Loop thru all channels corresponding to client robots. Check each
5051     // channel to see if we received a new map message.
5052     // Robot 2 is on channel 1, Robot3 is on channel 2, . . .
5053
5054     for (channel=1; channel < MAX_ROBOTS; channel++){
5055
5056         // Check for new map message
5057
5058         if (!receive_robot_message(channel, mapfile)) {
5059             continue;           // If nothing to read on this channel,
5060                                 // do not give up, continue will jump
5061                                 // back to "for" loop and increment
5062                                 // channel counter.
5063         }
5064
5065         cout << "New map from remote robot in <" << mapfile << ">." <<
5066 endl;
5067
5068         // Load grid along with position info
5069
5070         if (!load_grid_file_com(&remote_grid, mapfile, posinfo)) {
5071             return;
5072         }
5073
5074         sscanf(posinfo, "%d %d %d", &mx, &my, &mtheta);
5075
5076         cout << "New map position = (" << mx << ", " << my << ") [" <<
5077 mtheta << "]"
5078             << endl;
5079
5080         // Display and integrate new map
5081
5082         // grid_display(grid_window, remote_grid);
5083
5084         // NEW MAJOR SCOUT THESIS change below
5085         // if r.id==1 then robot is SERVER and needs to integrate a local scan
5086         // to the global map
5087         // if r.id !=1 then robot is CLIENT and needs to integrate the SERVER
5088         // global map that is sent
5089
5090         if (r.id==1) {
5091             integrate_grid(global_grid, remote_grid, (double) mx / 120.0,
5092                           (double) my / 120.0, (double) mtheta / 10.0);
5093         }
5094         else {

```



```
5095
5096     integrate_global_grid(global_grid, remote_grid, (double) mx /
5097 120.0,
5098     (double) my / 120.0, (double) mtheta / 10.0);
5099 }      // close for else r.id !=1
5100
5101     grid_display_global(global_grid);
5102
5103 }      // close for channel check counter
5104 // END SCOUT THESIS CHANGE
5105 }
```


APPENDIX I. FRONTIER-BASED EXPLORATION CODE – COMM.H

This appendix contains the header file for the communications routine that allows multiple robots to send messages to one another.

```
1  /* Original code written by William Adams */
2
3  /* Modifications for increased number of robots June 1998
4     for Master's Thesis work by Patrick A. Hillmeyer */
5
6  /* include file for comm.c and all files linking to comm.o */
7
8  enum { OFF_COMM, NONBLOCK_COMM, BLOCK_COMM } ;
9
10 #define PORT_DETECT 65003
11 #define PORT_GESTURE 65004
12 #define PORT_AUXPORT 65005
13 #define PORT_CONTSERV 65006
14 #define PORT_SEARCH 65007
15 #define PORT_CONTLOC 65008
16 #define PORT_ARIEL 65009
17
18 /* BEGIN SCOUT THESIS CHANGE */
19
20 #define MAX_ROBOTS 9 /* This is the max number of robots that can
21                      operate at one time - change as you get
22                      more robots - this must always be one less
23                      than MAXCHANNEL - see important note about
24                      MAXCHANNEL and comm.c file. */
25
26 #define SERVER_ROBOT 1 /* This is the ID number (in Nserver) of the
27                        robot that will act as the Server robot
28                        to the other Client robots for receiving and
29                        sending .eg files */
30
31 #define BASE_CLIENT_PORT 65007
32
33
34
35 /* IMPORTANT!! The initialization of global arrays sd, ld, and
36 comm_mode in the file comm.c has to match EXACTLY with MAXCHANNEL.
37 Example: if MAXCHANNEL is 10 then you need 10 zeros to initialize each
38 of the arrays mentioned above. */
39
40 #define MAXCHANNEL MAX_ROBOTS + 1
41 /* Any single process can communicate with this
42 many other processes. Although the port numbers
43 on both ends of the communication must agree,
44 the channel numbers do not need to agree.
45 Within a single process, each communication
46 link must have a unique channel number. */
47 /* If this is changed, you must change the initializing
48 declaration using it in comm.c */
49
50 /* END SCOUT THESIS CHANGE */
```


APPENDIX J. FRONTIER-BASED EXPLORATION CODE – COMM.C

This appendix contains the source code for the communications routine that allows multiple robots to send messages to one another.

```
1  /*****
2  * comm_server.c
3  * written: 11/22/95 William Adams
4  * last modified: 1/22/95 William Adams
5  *
6  * Set up internet communication on a single port.
7  * Receive requests from ONE other process and send back
8  * information.
9
10 *****/
11
12 /* Modifications for increased number of robots June 1998
13    for Master's Thesis work by Patrick A. Hillmeyer */
14
15 #include <stdio.h>
16 #include <sys/types.h>
17 #include <sys/socket.h>
18 #include <netinet/in.h>
19 #include <netdb.h>
20 #include <fcntl.h>
21 #include <errno.h>
22
23 #include "comm.h"
24
25 enum status { NOTHING_C, HALFWAY_C, READY_C };
26
27 // BEGIN SCOUT THESIS CHANGE
28 // *** see notes in comm.h file concerning these next few lines
29
30 int sd[ MAXCHANNEL ] = { 0,0,0,0,0,0,0,0,0,0 }; /* socket handle */
31 int ld[ MAXCHANNEL ] = { 0,0,0,0,0,0,0,0,0,0 };
32 int comm_mode[ MAXCHANNEL ] = { 0,0,0,0,0,0,0,0,0,0 };
33
34 // END SCOUT THESIS CHANGE
35
36 int haveaclient = 0;
37
38 /* wait client to call, blocking */
39 int comm_wait_for_client(channel,control
40 int channel,control;
41 {
42     if (comm_mode[ channel ] == NOTHING_C) {
43         fprintf(stderr,
44             "\nImproper call to comm_wait_for_client...use
45 init_comm_server.\n");
46         return(5);
47     }
48     else if (comm_mode[ channel ] == READY_C) {
49         fprintf(stderr,
50             "\nRedundant call to comm_wait_for_client, ignored\n");
51         return(0);
52     }
53 }
```



```

53
54 /* else comm_mode[ channel] == HALFWAY_C which is correct */
55
56 if ((sd[ channel] = accept( ld[ channel], 0, 0)) < 0) {
57     perror("INET Domain Accept");
58     return(5);
59 }
60
61 /* set to non-blocking if specified, else default is blocking */
62 if (control == NONBLOCK_COMM)
63     fcntl(sd[ channel], F_SETFL, O_NDELAY);
64
65 comm_mode[ channel] = READY_C; /* success */
66
67 return(0); /* success */
68 }
69
70
71
72 int init_comm_server(channel, port_num, control)
73 int channel, port_num, control;
74 {
75 // BEGIN SCOUT THESIS CHANGE
76     static int num_socs = 0; /* Number of sockets already established. */
77     int rc;
78     int addrlen;
79     struct sockaddr_in name;
80     struct sockaddr_in *ptr;
81     struct sockaddr addr;
82     struct hostent *hp, *gethostbyaddr();
83     int err;
84
85     // If you are the SERVER ROBOT, set up next available channel
86     // for the new client robot
87     if (port_num == PORT_ARIEL){
88         channel = ++num_socs;
89         port_num = BASE_CLIENT_PORT + num_socs + 1;
90     }
91 // END SCOUT THESIS CHANGE
92
93     /* create a "listen" socket to receive service requests */
94     if ((ld[ channel] = socket(AF_INET, SOCK_STREAM, 6)) < 0) {
95         perror("INET Domain Socket");
96         return(1);
97     }
98
99     /* initialize fields in an Internet address structure */
100     name.sin_family = (short int) AF_INET;
101     name.sin_port = htons(port_num);
102     name.sin_addr.s_addr = INADDR_ANY;
103
104     /* bind the Internet address to the Internet socket */
105     if (bind(ld[ channel], (struct sockaddr *)&name, sizeof(name)) < 0) {
106         close(ld[ channel]);
107         perror("INET Domain Bind");
108         return(2);
109     }
110

```

```

111     /* find out the port number assigned to our socket */
112     addrlen = sizeof(addr);
113     if ((rc=getsockname(lfd[ channel], &addr, &addrlen))<0) {
114         perror("INET Domain getsockname");
115         return(3);
116     }
117
118     /* now "advertise" the port number assigned to us */
119     ptr = (struct sockaddr_in *) &addr;
120     /* printf("\n\tSocket has port number: %d\n", ntohs(ptr->sin_port)); */
121
122     /* mark socket as a passive "listen" socket */
123     if (listen(lfd[ channel], 5)<0) {
124         perror("INET Domain Listen");
125         return(4);
126     }
127
128     /* wait for a client to contact us... (blocking) */
129     comm_mode[ channel] = HALFWAY_C;
130     if ((err=comm_wait_for_client(channel, control)) != 0) {
131         return(err);
132     }
133
134     /* find out who's calling us */
135     /* if ((rc=getpeername(sfd[ channel], &addr, &addrlen))<0) {
136         perror("INET Domain getpeername");
137         return(6);
138     } */
139
140     /* "announce" the caller */
141     /* printf("\n\tCalling socket from host %s\n", inet_ntoa(ptr->sin_addr));
142     printf("\n\t      has port number %d\n", ptr->sin_port);
143     if ((hp=gethostbyaddr(&ptr->sin_addr, 4, AF_INET)) != NULL) {
144         printf("\tFrom hostname: %s\n\tWith aliases:", hp->h_name);
145         while (*hp->h_aliases)
146             printf("\n\t\t\t%s", *hp->h_aliases++);
147         printf("\n\n");
148     }
149     else {
150         perror("\n\tgethostbyaddr() failed");
151         printf("\n\tthe_errno is %d\n\n", h_errno);
152     } */
153
154     comm_mode[ channel] = READY_C;
155     return(0);
156 }
157
158
159
160 int init_comm_client(channel, mach_name, port_num, control)
161 int channel;
162 char *mach_name;
163 int port_num, control;
164 {
165     struct sockaddr_in name;
166     struct hostent *hp, *gethostbyaddr();
167
168     /* create a "client" socket to request service */

```

```

169     if ((sd[ channel]=socket(AF_INET,SOCK_STREAM,0))<0) {
170         perror("INET Domain Socket");
171         return(1);
172     }
173
174     /* initialize fields in an Internet address structure */
175     name.sin_family = AF_INET;
176     name.sin_port = htons(port_num);
177     hp=gethostbyname(mach_name);
178     memcpy(&name.sin_addr.s_addr, hp->h_addr, hp->h_length);
179
180     if (connect(sd[ channel], (struct sockaddr *)&name, sizeof(name))<0) {
181         perror("Connect()");
182         return(2);
183     }
184
185     /* set to non-blocking if specified, else default is blocking */
186     if (control==NONBLOCK_COMM)
187         fcntl(sd[ channel], F_SETFL, O_NDELAY);
188
189     comm_mode[ channel] = READY_C; /* success */
190     return(0);
191 }
192
193
194
195 int read_comm(channel,buf,bufsize)
196 int channel;
197 char *buf;
198 int bufsize;
199 {
200     int nbytes;
201
202     // BEGIN SCOUT CHANGE
203     // If no socket has been established on this channel,
204     // then return.
205     if (sd[ channel] == 0){
206         return(0);
207     }
208     // END SCOUT CHANGE
209
210     if (comm_mode[ channel] == READY_C) {
211         memset(buf,0,bufsize);
212         if ((nbytes=read(sd[ channel],buf,bufsize))<0) {
213             if (errno!=EWOULDBLOCK) {
214                 perror("INET domain Read");
215                 return(-1); /* indicate error */
216             }
217             else /* it was just an unblocked read with no data ready */
218                 return(0);
219         }
220         else if (nbytes==0) {
221             fprintf(stderr, "\nSender Disappeared.\n");
222             comm_mode[ channel] = HALFWAY_C;
223             return(-2); /* no data to be read */
224         }
225         else {
226             return(nbytes); /* read data */

```

```

227     }
228 }
229     else /* socket has not been initialized */
230         return(-3);
231 }
232
233
234 void write_comm(channel,buf,bufsize)
235 int channel;
236 char *buf;
237 int bufsize;
238 {
239     if (comm_mode[ channel] == READY_C)
240         write(sd[ channel] ,buf,bufsize);
241 }
242
243
244
245 demoserver() /* demo */
246 {
247     int a=0;
248     int b=10;
249     int c=100;
250     char buf[ 256] ;
251
252     init_comm_server(0,65003,NONBLOCK_COMM);
253     while (1) {
254         if (read_comm(0,buf,sizeof(buf))>0) { /* if read something */
255             sprintf(buf,"%d %d %d\n",a++,b++,c++);
256             write_comm(0,buf,sizeof(buf));
257         }
258         sleep(1);
259     }
260 }
261
262
263 democlient()
264 {
265     int a,b,c;
266     char buf[ 256] ;
267
268     init_comm_client(0,"coyote",65003,BLOCK_COMM);
269     while (1) {
270         strcpy(buf,"Request");
271         write_comm(0,buf,sizeof(buf));
272         read_comm(0,buf,sizeof(buf));
273         sscanf(buf,"%d %d %d",&a,&b,&c);
274         printf("\nreceived %d %d %d\n",a,b,c);
275         fflush(stdout);
276         sleep(1);
277     }
278 }

```


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